# Bulletin

# of

# The Geological Society of America

VOLUME 65 October 1954 NUMBER 10

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Subscription $15.00 per year.

Printing Office: Mt. Royal & Guilford Aves., Baltimore 2, Md.

Communications for publications should be addressed to The Geological Society of America. Dr. H. R. Aldrich, Secretary, 419 West 117 Street, New York, N. Y.

Please give notice of change of address 4 weeks in advance. Claims for non-receipt of the Bulletin of a given month must be sent to the Secretary of the Society before the end of the second succeeding month.

Entered as second-class matter at the Post-Office at Baltimore, Md., under the Act of Congress of July 16, 1894.

Accepted for mailing at special rate of postage provided for in Section 1103 Act of October 3, 1917, authorized on July 8, 1918.

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 65, PP. 941-956, 4 PLS. OCTOBER 1954

# TRANSPACIFIC DETECTION OF MYOJIN VOLCANIC EXPLOSIONS BY UNDERWATER SOUND

BY R. S. DIETZ AND M. J. SHEEHY

## ABSTRACT

On 17 September 1952 a fishing boat, the MYOJIN MARU, discovered a submarine volcanic eruption 200 nautical miles south of Tokyo. The volcano appears to be the central cone of a caldera lying along the Fuji volcanic zone. The near-by Bayonnaise Rocks mark the highest, and the only subaerially exposed, portion of the caldera rim. A series of great explosions accompanied the extrusion of augite-hypersthene dacite. Since 26 September, when the main series of explosions ended, there has been only sporadic activity.

Because of its remoteness, only a few visual observations of Myojin were made. Additional data were obtained from a tsunami recorder on Hachijo Island, 130 kilometers north of Myojin, which detected several tsunamis initiated by the volcanic eruptions, and by an atmospheric electricity recorder at Tokyo which detected atmospherics associated with the eruption. In contrast, a rather complete record of the Myojin activity was recorded by the U. S. Navy Sofar stations at Point Sur and Point Arena, California, about 8600 kilometers from the scene. More than 100 explosions were detected, one of which lasted for more than an hour. Explosions recorded on Sofar equipment agree in time with those observed visually or inferred from tsunami and atmospherics data.

From the tsunami data and the Sofar records, it was independently concluded that the explosion which destroyed the Japanese Hydrographic vessel, No. 5 KAIYO MARU, occurred at about 1220 JST on September 24. All 31 people aboard the vessel were lost.

This is believed to be the first time any signals on Sofar records have definitely been identified as of volcanic origin, and, since some of the signals were distinctive, installations similar to those of Sofar stations may prove of value for monitoring oceanic volcanic activity.

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## Introduction

On September 18, 1952, the U. S. Navy Sofar (Sound Fixing and Ranging) Stations at Point Sur and Point Arena, California, received a series of signals of particularly high intensity and long duration. The signals arrived at the Point Arena Station 3 minutes 10 seconds earlier than at Point Sur; this established the locus of the source as somewhere on a path extending across the North Pacific from a point slightly north of San Francisco and passing about 200 nautical miles south of Tokyo. The signals were not received at the Kaneohe station on Oahu Island, Territory of Hawaii. It was thus evident that the source had been west of the 180th meridian, because the hydrophones are shadowed by Oahu for signals coming from the far west. U. S. Navy personnel at Point Sur reported that the signals had sounded like a series of closely spaced, distant explosions, and that similar signals, although of lower intensity and shorter duration, were still being received.

Nothing like these large signals had ever been received at any station, and there was considerable speculation as to possible sources of them until a few days later when press releases carried the information that a submarine volcano about 200 nautical miles south of Tokyo had been observed in eruption on 17 September. Evidently this eruption was the source of the signals.

The visual observations were made from the Japanese fishing boat Myojin Maru No. 11; this periodically active volcano was christened "Myojin" (pronounced Mee-oh'-gin) in recognition of this boat. Myojin, appropriately, means Bright God in Japanese. The shoal water area formed by Myojin Volcano is termed "Myojin Sho" (Myojin Reef). The island which has formed three times and disappeared twice as of the present writing (May 1953) is called "Myojin Jima" or Myojin Island.

The present paper reviews briefly the geologic setting of Myojin and the history of volcanic activity in that region, describes the September 1952 eruption, correlates the Sofar observations with those made by other methods, and discusses certain possibilities suggested by this work.

## Acknowledgments

The correlation of the Sofar data with the Japanese observations on Myojin was made possible through a Fulbright research award granted to Dietz; this award allowed him to work in Japan for 12 months. Many Japanese scientists generously co-operated in the project. Especially appreciated is the close interest and assistance provided by Dr. K. Suda, Chief of the Japanese Hydrographic Office; the assistance of Dr. H. Niino, marine geologist of the Tokyo College of Fisheries, who made two cruises to Myojin and who is responsible for many of the visual observations on the volcano; and the assistance of Dr. E. Nakano of the Japanese Central Meteorological Observatory who provided the tsunami data. The paper has also received inspiration from the memory of Dr. R. Tayama, eminent Japanese marine geologist who was lost aboard the Kaiyo Maru while surveying Myojin on September 24, 1952. The Tokyo office of the U. S. Geological Survey under S. K. Neuschel has given valuable assistance. The co-operation of Helen Foster, Charles Johnson, and George Veile, all of that office, is gratefully acknowledged.

## Geologic Setting and History of Eruptions near Myojin Reef

On the morning of 17 September 1952 the Myojin Maru radioed that a new island was being formed at 139° 59.5′ E. and 31° 56.8′ N., east of Bayonnaise Rocks, the nearest point of land (Fig. 1). Myojin volcano is apparently the central cone of a submarine caldera about 10 km. in diameter. The Bayonnaise Rocks mark the highest part of the caldera rim (somma), and they are the only other portion of the seamount above sea level. This caldera forms the summit of a submarine volcano 4500 feet high resting on an island-arc ridge which lies west of the Japanese Trench. The submarine volcano lies along the Fuji volcanic zone which crosses the Fossa Magna, a structurally deranged zone which can be thought of as the "broken back" of Japan, and extends through the Izu Peninsula to O Shima, Miyake Shima, Mikura Jima, Hachijo Jima, Ao-go Shima, the Bayonnaise Rocks, Smith Rocks, Tori Shima,

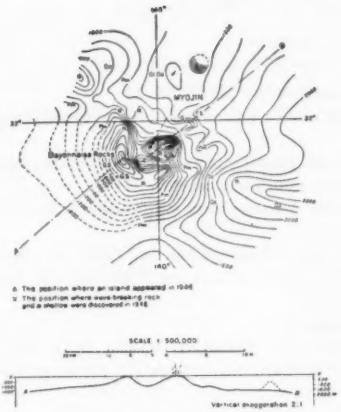



FIGURE 1.—SUBMARINE TOPOGRAPHY OF AREA NEAR MYOJIN VOLCANO
(Adapted from Mita, 1949)

certain. Table 1 contains a history of the eruptions at or near Myojin from 1896 to 1946.

The fundamental structure in the vicinity of Myojin is a downbuckling of the earth's crust, or tectogene, the axis of which is approximately under the axis of the Japan Trench. Myojin appears to be superimposed on a geanticline 100 mi. west of and parallel to the tectogene. A second north-south row of apparently volcanic seamounts is present 60 miles west of Myojin. This may mark the position of a second geanticline.

In the 1952 eruptions augite-hypersthene dacite was extruded. Such acidic lavas are viscous and commonly high in volatiles, so that eruptions of such lavas tend to be explosive.

## MYOJIN ERUPTION, 1952

### *Visual Observations*

Myojin Reef is remotely situated, so that visual observations were obtained only sporadically. These were made by fishing boats and by vessels and aircraft dispatched especially to see the eruption (Table 2). Japanese Standard Time is used in the Table; nine hours must be subtracted to get Greenwich Civil Time.

TABLE 1.—HISTORY OF ERUPTIONS AT OR NEAR MYOJIN PRIOR TO 1952 (MITA, 1949)

| Date | Position | Remarks |
|---|---|---|
| 1896 | 7.5 mi. E. of Bayonnaise Rocks | Wave-breaking reef |
| 1896 April | Unknown | Eruption |
| 1915 February | 6 mi. E. of Bayonnaise Rocks | Submarine reef 10 m deep |
| 1915 April | 6 mi. E. of Bayonnaise Rocks | Submarine eruptions |
| 1915 June–July | 10–20 mi. E. of Bayonnaise Rocks | Submarine eruption |
| 1934 May | 5 mi. E. of Bayonnaise Rocks | Sea turned yellow; smell of sulfur |
| 1946 February | Near Bayonnaise Rocks 31° 57′ N 140 01′ E | New island formed 200 x 150 m |
| 1946 April | 31° 57′ N 140 01′ E | Spine-shaped island 36 m high* |
| 1946 October | 31° 57′ N 140 01′ E | Island 100 m high |
| 1946 December | 31° 57′ N 140 01′ E | Wave breaking over a reef; no island. |

* Spine-shaped island seen in April 1946, apparently Pelée spine type, *i.e.*, a solidified lava plug ejected from throat of volcano. Its destruction by September must be ascribed to explosion or to crum bling. Sub sidence may also have played a part, but effect of wave action must have been negligible over short period of life of island.

and the Kazan Retto. Plate 1 shows the regional setting of Myojin and the Fuji volcanic zone.

Frequent eruptions have occurred at or in the vicinity of Myojin, and it has become known as a place where volcanic islands form and disappear. There are probably several volcanic vents in the vicinity of Myojin which have been active, but positions at sea are difficult to determine accurately so that the presence of more than one active vent is not

### *Tsunami Records*

A wave recorder installed on Hachijo Island, 130 km. north of Myojin, recorded several

TABLE 2.—VISUAL OBSERVATIONS OF MYOJIN ERUPTION, 1952

| Time | Date | Remarks |
|---|---|---|
| 0725 | 9/17 | Eruption discovered by fishing boat MYOJIN MARU No. 11. |
| 1839–1857 | 9/17 | Myojin visited by Japanese aircraft and reported erupting. Large explosions not seen. |
| 0700–0800 | 9/18 | Myojin visited by Japanese aircraft. Photographs show great steam column indicating effusion of lava; no large explosion observed. |
| 0800–1000 | 9/18 | Myojin visited by Maritime Safety Agency patrol craft SHIKINE MARU. Small explosion photographed at 0920. |
| 1600 | 9/18 | Aerial photo (U. S. Navy) shows great steam column (*see* LIFE Magazine, October 13, 1952, p. 129) like that observed between 0700–0800. No large explosions seen. |
| 1734 | 9/21 | CHIKUBU MARU saw a violent explosion. |
| 1200–1240 | 9/22 | Myojin visited by S. K. Neuschel, U. S. Geological Survey, and several other scientific observers aboard U. S. Air Force plane. Myojin quiet except for small steam clouds. |
| 0900 | 9/22 | Airplane "Soyokage" of Asahi Press saw three violent explosions. |
| 1500– to 1900– | 9/22 9/23 | Myojin visited by Tokyo College of Fisheries ship, SHIN'YO MARU. Several scientists aboard including H. Niino. Explosions carefully recorded and photographed (Niino, 1952). |
| 1500 | 9/22 | While SHIN'YO MARU was at Hachijo Island, 130 km north of Myojin, a large cloud rose suddenly on horizon to the south at about 1500 and disappeared after 10 min. This cloud apparently caused by an explosion of Myojin. |
| 2345–2355 | 9/22 | A fire pillar observed when SHIN'YO MARU was near Ao-go Shima, 32 mi. north of Myojin. This presumably associated with an explosive eruption. |
| 0834 | 9/23 | Large explosion observed by SHIN'YO MARU from a distance of 5 mi. (Pl. 1). Explosion lasted 3.5 min. and the explosion cloud lasted 20 min. The energy of this explosion was estimated to be about $10^{18}$ ergs by S. Murauchi (1952). |
| 1312 | 9/23 | SHIN'YO MARU observed and photographed a moderate explosion from a distance of 1 mi. (Pl. 2). Explosion lasted 2.0 min. and explosion cloud lasted for 25 min. No shock wave was felt (Pl. 2). |
| 1340 | 9/23 | SHIN'YO MARU observed and photographed a moderate explosion from a distance of 0.8 mi. (Pl. 3). Explosion lasted 2.0 min. and the cloud lasted 25 min. A roaring sound was heard and the ship felt a strong shock wave. This is the only explosion reported as being heard by any observers. |
| 1900 | 9/23 | SHIN'YO MARU observed a large explosion from a distance of 7 miles. Explosion lasted 2.5 min. and the cloud persisted for 30 min. |
| 0540 | 9/24 | Fishing boat UMITAKA MARU reported an explosion of Myojin. |
| ..... | 9/24 | Maritime Safety Agency's KAIYO MARU No. 5 visited Myojin. Nature of observations unknown except that a large explosion occurred which destroyed KAIYO MARU along with all hands. |
| 1330 and 1830 | 9/25 | NISSHO MARU No. 3 reported explosions of Myojin. |
| 0545 and 0800 | 10/3 | Patrol boat MUROTO reported Myojin to be erupting. |
| 0950 | 10/21 | MATSUA MARU No. 5 saw small explosion 30 meters high. |

tsunamis clearly related to explosions of Myojin, thus adding to the record of its activity. Unfortunately, the wave recorder was not in continuous operation, and the data are incomplete (Table 3).

Niino's (1952, p. 23) description of the formation of the tsunami wave associated with the explosion of 1340 on September 23 is noteworthy. According to him the water above Myojin swelled into a dome 5 meters high and 200 meters wide. Instantly water began to fall outward from the dome like a waterfall. Then the central part of the water dome was pushed up into a serrated form to a height of from 30

to 60 meters. A black mass of volcanic debris protruded from the water mass, and, in an instant, the water and the black mass became one. Intense noise and air concussion took place during the explosion.

could be identified. The times of the atmospherics, and the eruption times at Myojin based on visual observations and on some of the Sofar data are shown in Table 4.

From Table 4 it is apparent that in general

TABLE 3.—TSUNAMI RECORDS OF 1952 MYOJIN EXPLOSIONS

| Date | Hours of Wave Recorder Operation | Remarks |
|---|---|---|
| 9/16 | 1055–1533 | Tsunami at Hachijo from 1220–1245. Microseism recorded at Hachijo at 1152. Travel time for sea wave thus appears to be 28 min. |
| 9/17 | not operated | Tsunami seen by eye at Hachijo 0700–0900. Time approximate. |
| 9/18 | 0912–1612 | No tsunami recorded. |
| 9/19 | 1045–1502 | No tsunami apparent but, if one occurred, it would probably be obscured by big swells present on this day. |
| 9/20 | 1026–1611 | No tsunami. |
| 9/21 | 1007–1442 | No tsunami. |
| 9/22 | Recorder not operated. | |
| 9/23 | 1030–1510 | Tsunami from 1350–1425. Tsunami observed by SHIN'YO MARU in connection with 1340 explosion. At distance of 0.8 mi. from Myojin, waves 2 m high and 50 m long observed. Period not measured. |
| 9/24 | 1013–1828 | Tsunami from 1253–1408 at Hachijo. Maximum amplitude 1.4 m. Wave period 39 sec. Mean period 62 sec. Longest wave came first. From the wave distribution, Nakano (personal communication) calculated an initial uplifted dome of water 2 km in diameter. |
| 9/25 | Recorder not operated. | |
| 9/26 | 1018–1548 and 1630–2400 | Tsunami 1303–1438 at Hachijo. Max. amplitude 1.4 m. Max. period 90 sec.; mean period 68 sec.; minimum period 35 sec. Explosion seen by SHIKINE MARU at 1235; hence travel time to Hachijo is 28 min. |
| 9/27 to 10/1 | | Wave recorder operating about half of each day but no tsunamis recorded. |

*Atmospherics Accompanying Eruption*

As is commonly the case during volcanic eruptions, thunder and lightning were occasionally observed by those who witnessed the Myojin eruption. Atmospheric electricity in the 300 kc/sec region was observed during the 1951 eruption of Mt. Mihara on O Shima, about 60 nautical miles south of Tokyo. T. Inoue, who monitored for atmospherics in this frequency region during the period 10 September to 10 October 1952, found that some strong continuous atmospherics corresponded to the eruption at Myojin. His antenna consisted of two loops oriented at right angles so that atmospherics arriving from the direction of Myojin there is good agreement between the atmospherics data and the visual and Sofar data. The detection of atmospherics shortly before midnight on 15 September suggests that the eruption of Myojin may have begun at least an hour before the first explosion detected by the Sofar stations, namely 0040 on 16 September. Visual observations during 17 September and on the morning of 18 September showed that lava was being extruded quietly, thus producing a large steam cloud, but no large explosions were seen. This explains therefore, why no explosion was detected at the Sofar station which could be correlated with the atmospherics detected at 1503 and 1517 on 17 September.

*Sofar Detection of Explosions*

The principles of long-range transmission of sound from underwater explosive sources, and the main features of a Sofar installation, have appeared in literature (Ewing *et al.*, 1946; Ewing and Worzel, 1948; Luskin, *et al.*, 1952; Stifler and Saars, 1948), in the press, and on radio and television, so that these matters need not be treated here in detail. A brief résumé seems in order, however, for the benefit of those still unfamiliar with this field.

TABLE 4.—CORRELATION OF ATMOSPHERICS WITH VISUAL AND SOFAR OBSERVATIONS OF EXPLOSIONS

| Date (1952) | Time of Atmospherics J.S.T. | Visual Observation of Explosion | Sofar Detection* of Explosion |
|---|---|---|---|
| 15 Sept. | 2320–2348 | ..... | None |
| 16 Sept. | 1206 | ..... | 1151 |
| 17 Sept. | 1503, 1517 | ..... | None |
| 18 Sept. | 2223–26 2245–2301 | ..... | 2010–2130 |
| 19 Sept. | 1434–1501 | ..... | 1436 |
| 20 Sept. | 1356–1402 | ..... | 1400 |
| 20 Sept. | 1629, 1655–1700 | ..... | 1650 |
| 21 Sept. | 1352, 1357–1408 | ..... | 1400 |
| 21 Sept. | 1426–40–45 | ..... | 1435 |
| 22 Sept. | 1516–18, 1524–27, 1532–33, 1539–43 | ..... | 1531 |
| 22 Sept. | Equip. not operating | 2345 | 2345 |
| 23 Sept. | 0804–37 | 0834 | 0834 |
| 23 Sept. | 1227–38 | 1235 | 1234 |
| 3 Oct. | 0550 | 0545 | 0531 |

* Travel time for underwater signals has been subtracted from time at which signals were received.

The transmission of underwater explosive signals over great distance is made possible by the nature of the vertical distribution of sound velocity in the deep ocean. The velocity decreases with depth until a minimum value is reached, at a depth of approximately 2400 feet in the mid-latitude regions of the Pacific (Anderson, 1950), and then increases with depth from this point to the bottom. This velocity structure results in refraction of sound energy in such a manner that some of it is transmitted over deep ocean paths without suffering losses due to bottom or surface reflections. (Seamounts, or shoal regions along the travel path, will of course intercept some of the energy and diminish the resultant signal amplitude.) The intensity of this channeled sound decreases only as the first power of the range plus an absorption factor, and, since the absorption in the low-frequency region is very small, one can detect explosive signals in the ocean at great ranges.

Listening stations making up a Sofar network are designed to take advantage of this transmission in fulfilling the network's purpose, that of locating persons in distress at sea[1]. Ships and aircraft operating in areas covered by a Sofar network are provided with a small bomb (Bureau of Ordnance, not dated) containing 4 pounds of T.N.T. and set for detonation near the depth of minimum sound velocity. The sound signal produced by the explosion of this bomb is detected at the Sofar stations, and the location of the source determined by a triangulation procedure based on the differences of signal-arrival times among the three stations. The inherent accuracy of location by the present method is about 3 miles.

Each Sofar station consists basically of a group of crystal hydrophones mounted in a stainless-steel cage on the continental slope at the depth of minimum sound velocity. Several miles of submarine cable are used to connect the hydrophones to recording equipment on shore. At the shore end of the cable the incoming signals are amplified, passed through a 500-cycle-per-second lowpass filter, rectified, logarithmically amplified, and then recorded as power levels on a drum recorder. A timing trace is recorded adjacent to the signal trace and calibrated daily against official radio time signals in order to make possible the accurate determination of signal-arrival time. In the case of typical long-range Sofar signals, the arrival time can be determined with an accuracy of 0.2 second. On the Sofar records, the timing trace appears beneath the signal trace, and the timing marks are 1 second apart.

Since the stations are in operation 24 hours a day, a continuous record is available of low-frequency sounds originating in the sea. The

[1] There is no Sofar network currently in operation.

maximum range at which such sounds can be detected depends of course upon the magnitude of the source and the nature of the travel path. Signals from the 4-pound Sofar bombs in the Pacific have been detected readily at a range of 8000 km., and a T-phase has been received from an earthquake at a range of 9819 km. (Ewing *et al.*, 1951).

The most nearly complete record of the explosive activity of Myojin was obtained by the Pacific Sofar stations. The good correlation (Table 4) between the atmospherics data and a few of the visual and Sofar observations, plus that shown in more detail between the Sofar data and the visual and tsunami observations, leaves no doubt that the signals received at Point Arena and Point Sur originated at Myojin. This is believed to be the first time any signals at Sofar stations have been definitely identified as being of volcanic origin, although Ewing *et al.* (1946) heard some sounds at a single installation in the Atlantic which were believed to originate in submarine volcanic activity. They pointed out that it was highly probable that submarine eruptions might be heard and located once a Sofar listening system was in operation.

A summary of the signals received is given in Table 5 and presented graphically on Figure 2. The time is given only to the nearest minute and is that of the signal origin at Myojin in Japanese Standard Time. A travel time of 1 hour 37 minutes 32 seconds, based on an assumed average horizontal velocity of 4830 feet per second and a computed distance to the Point Sur station of 8600 km., was used in obtaining the origin time from the Sofar records.

The acoustic signals are represented (Fig. 2) by vertical lines or rectangles, with the height indicating the relative size or intensity of the signals, and the width showing the duration of the intervals during which signals were received. The intensity scale is qualitative and rather crude, based simply on a visual estimate of the signal-to-noise ratio. A value of 1 indicates a signal-to-noise ratio of less than 10 decibels; 2 means a ratio of 10–20 decibels; 3, 20–30; 4, 30–40; and 5 indicates a signal-to-noise ratio of more than 40 decibels. Although only 77 lines or rectangles are shown (Fig. 2), over 400 individual signals were received. It would be impossible on any reasonably sized graph to plot all the signals.

Much of the visual and tsunami data have also been entered to show the correlation between the different sources of information. In the tsunami data, however, the times shown are reception times at Hachijo Island. The signals detected at the Sofar stations are in excellent agreement in time with visually observed explosions and with tsunamis recorded at Hachijo.

A rather complete history of the Myojin explosions can be gathered from Table 5 and Figure 2. Although Myojin was not observed in eruption until the morning of September 17, the Sofar stations received a signal originating at Myojin on September 16. Very possibly there were eruptions even before this which were not large enough to be detected at the distant stations. The atmospherics data indicate that activity had begun at Myojin at least as early as the evening of 15 September.

After the weak signal at 0040 on 16 September, a strong explosion occurred at 0912. This is believed to be the first of the main series of explosions and groups of explosions which lasted until 1235 on 26 September.

Six explosions took place from late morning to early evening of 16 September at about 2-hour intervals. Four explosions, none of which were of large magnitude, occurred on 17 September. The longest group commenced at 0611 and lasted 15 minutes. The explosions attained their greatest frequency and intensity on 18 and 19 September. During the morning of 18 September, the Sofar stations recorded nine explosions or series of explosions, most of them short. A Japanese aircraft visited the eruption between 0700 and 0800 and photographed a huge column of steam indicating that lava was being extruded quietly. No large explosions were seen, however, and one small signal was received by the Sofar stations corresponding to an origin time of 0704. No explosions were recorded in the late morning and early afternoon, and no tsunamis were recorded by the Hachijo Island wave recorder which was operated during part of this interval.

Explosive activity reached a climax on the evening of 18 September. A series of very strong explosions began at 1712 and lasted for almost 1 full hour. Another series com-

TABLE 5.—UNDERWATER SOUND SIGNALS RECEIVED AT PACIFIC SOFAR STATIONS FROM MYOJIN EXPLOSIONS

| Date (Japan 1952) | Calculated Explosion Time (Nearest Minute) Japanese Standard Time | Intensity | No. of Explosions and Duration of Received Signal, or Interval Covered by Series of Signals |
|---|---|---|---|
| 16 Sept. | 0040 | 1 | ..... |
| | 0912 | 3 | 3 explosions |
| | 1031 | 3 | 3 explosions |
| | 1152 | 2 | 1 explosion, 1 min. |
| | 1410 | 3 | 1 explosion, 2½ min. |
| | 1752 | 4 | 3 explosions, 2½ min. |
| | 1940 | 3 | 2 explosions, 1 min. |
| 17 Sept. | 0304 | 2 | 1 explosion |
| | 0611 | 2 | 10 explosions, 15 min. |
| | 1951 | 2 | ..... |
| | 2230 | 3 | ..... |
| 18 Sept. | 0120 | 3 | 4 explosions, 1 min. |
| | 0323 | 4 | 1 explosion, 1½ min. |
| | 0327 | 3 | 1 explosion, ½ min. |
| | 0444 | 3 | 1 explosion, ⅓ min. |
| | 0526 | 3 | intermittent explosions, 10 min. |
| | 0621 | 2 | 1 explosion, ⅓ min. |
| | 0704 | 2 | 1 explosion, ¼ min. |
| | 0803 | 3 | 1 explosion, ⅓ min. |
| | 0920 | 2 | ..... |
| | 1712 | 5 | First major explosion, 12 min. (*see* Fig. 4) |
| | 1735 | 4 | 4 explosions, 1 min. |
| | 1844 | 3 | 2 explosions, 1 min. |
| | 1946 | 3 | 14 explosions, 13 min. |
| | 2005 | 5 | Main series of explosions, 70 min. (*see* Fig. 5) |
| | 2131 | 3 | 2 explosions, ½ min. |
| 19 Sept. | 0029 | 2 | 50 moderate explosions, 80 min. |
| | 0425 | 2 | 7 min. |
| | 0902 | 2 | 2 explosions, 3 min. |
| | 1015 | 3 | 15 explosions, 20 min. |
| | 1240 | 2 | several small explosions, 1 hour |
| | 1436 | 3 | 1 explosion |
| | 1639 | 2 | 1 explosion |
| | 1805 | 2 | ..... |
| | 2048 | 2 | 4 explosions, ½ min. |
| | 2057 | 2 | many small explosions, 1 hour |
| 20 Sept. | 0613 | 3 | 2 min. |
| | 1312 | 3 | small explosions, 7 min. |
| | 1400 | 3 | 2 explosions, ½ min. |
| | 1649 | 5 | 10 explosions, 6 min. |
| | 1819 | 3 | 1 explosion, 15 min. |
| | 1850 | 3 | 13 explosions, 75 min. |
| 21 Sept. | 0111 | 2 | ..... |
| | 0213 | 2 | 4 explosions |
| | 0447 | 4 | 3 explosions, 15 min. |
| | 0529 | 4 | 25 explosions, 35 min. |
| | 1400 | 3 | ..... |
| | 1433 | 3 | 2 explosions |
| | 1507 | 1 | ..... |
| | 1737 | 3 | ..... |
| | 2324 | 3 | 1 min. |
| 22 Sept. | 0341 | 3 | 1 min. |
| | 0653 | 2 | 1 explosion, ⅓ min. |
| | 0914 | 3 | 1 explosion, ½ min. |
| | 1237 | 3 | series of moderate explosions, 45 min. |
| | 1530 | 3 | 7 explosions, 4 min. |
| | 1931 | 2 | ..... |
| | 2027 | 2 | 25 small explosions |
| | 2345 | 4 | 1 explosion, 1 min. |
| 23 Sept. | 0025 | 2 | 1 min. |
| | 0828 | 2 | ..... |
| | 1143 | 3 | 10 min. |
| | 1308 | 2 | ..... |
| | 1335 | 2 | ..... |
| | 1901 | 3 | 2 explosions, 1 min. |
| | 1914 | 2 | 4 explosions, 1½ min. |
| | 2233 | 2 | 1 min. |

TABLE 5.—*Continued*

| Date (Japan 1952) | Calculated Explosion Time (Nearest Minute) Japanese Standard Time | Intensity | No. of Explosions and Duration of Received Signal, or Interval Covered by Series of Signals |
|---|---|---|---|
| 24 Sept. | 0148 | 1 | ..... |
| | 0539 | 3 | 3 explosions, 1 min. |
| | 0552 | 3 | 3 explosions, 1 min. |
| | 1221 | 3 | 2 explosions, (most likely sank KAIYO MARU) |
| 25 Sept. | 0618 | 3 | several explosions, 1 min. |
| | 1316 | 3 | 2 explosions, 1 min. |
| | 1823 | 3 | 4 explosions, 1½ min. |
| 26 Sept. | 0104 | 3 | 1 explosion, ⅓ min. |
| | 1234 | 4 | 1 explosion, 1 min. (Final large explosion) |

menced at 1946, built up to a maximum at 2010, and then continued almost unabated for 70 minutes (Figs. 3, 4). Considering both intensity and duration, the signal beginning at 2007 and lasting for 33 minutes was the largest signal ever received by a Pacific Sofar station.

Large explosions continued to be received during 19 September. Several long series of explosions occurred during the day. About 50 moderate explosions were recorded over an 80-minute period beginning at 0029, and a series of small explosions took place beginning at 1240. Another group of small explosions started at 2057.

Activity diminished somewhat on 20 September. The greatest outburst began at 1852 with about 12 moderate explosions over a period of about 1 hour.

On September 21 several explosions took place in the early morning hours. They reached a climax at 0529 when 25 large explosions occurred over a 35-minute interval. Five other explosions took place in the afternoon and evening. None of the explosions on September 20 and 21 were seen, nor did the tsunami recorder detect them.

September 22 and 23 constitute a period of reliable visual observations. A U. S. Air Force plane with S. K. Neuschel of the U. S. Geological Survey and several other scientists aboard visited the scene on 22 September, and the Tokyo College of Fisheries Ship, SHIN'YO MARU, with H. Niino and several other scientists aboard, was at or near the site during September 22 and 23.

According to the Sofar data there were eight explosions on 22 September. The main activity was at 1237 when a series of moderate explosions occurred lasting 45 minutes. The U. S. Air Force plane made several low passes taking photographs over Myojin between 1200 and 1230. The photographs showed only a few rocks above sea level from which a little steam was issuing. At 1531 there was a series of seven explosions over a 4-minute period. This may have been the series that formed the explosion cloud seen from Hachijo Island "at about 1500" (Niino, 1952). The Sofar stations recorded a single large explosion which began at 2345, and which can be correlated with a "pillar of fire" seen by Niino from 32 miles north of Myojin commencing at 2345 and lasting 20 minutes.

According to the Sofar data there was a moderate explosion at 0025 on 23 September. At 0834 a large explosion (Pl. 2) was photographed in detail by Sugano of the Asahi Press. This explosion caused only a moderate-sized acoustic signal at the Sofar stations. According to the Sofar records the next activity consisted of a series of fairly large explosions lasting approximately 10 minutes and starting at 1143.

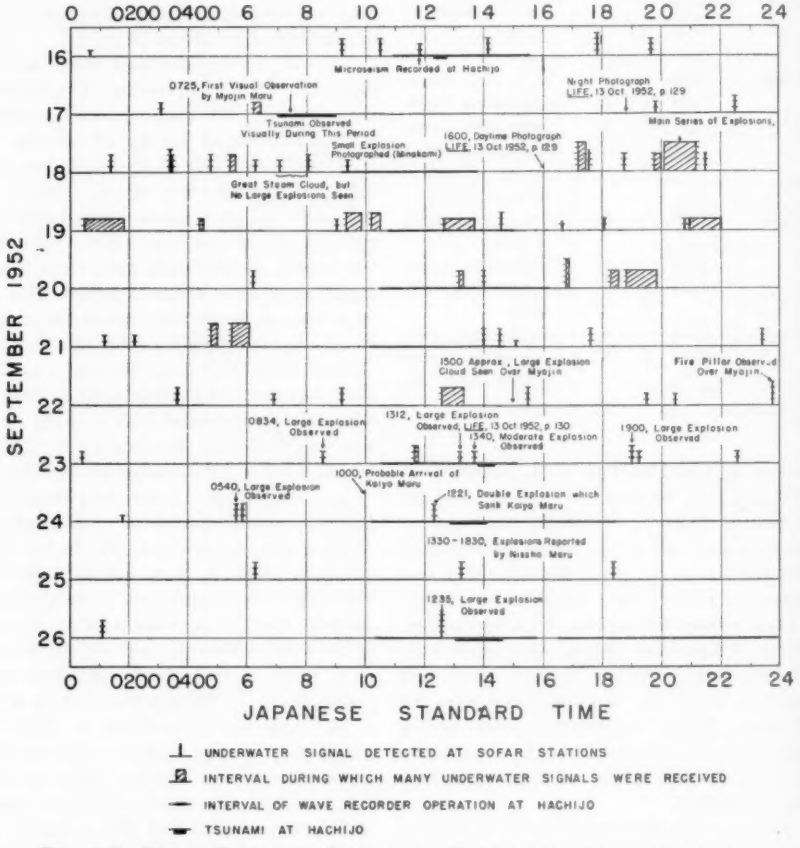
The large explosion shown on Plate 3 occurred at 1312. This explosion also was photographed by Sugano from a distance of only 1 mile and with the use of a telephoto lens. At 1340 a second explosion (Pl. 3, fig. 2) took place. Moderate acoustic signals were received at the Sofar stations from both explosions, and a tsunami was recorded at Hachijo Island apparently as a result of the 1340 explosion. Strangely enough, this explosion was the only one reported heard on board the SHIN'YO MARU.

Signals were next received at the Sofar stations corresponding to origin times at Myojin of 1901 and 1914, and the SHIN'YO MARU observed the first of these from a distance of 7 miles as she was departing from the site. The final explosion on this day took place at about 2233.

Activity diminished on September 24; only four explosions were recorded. An explosion at 0539 as recorded by Sofar was seen by the UMITAKA MARU which reported an eruption at 0540. A double explosion at 1221 apparently was responsible for the destruction of the KAIYO MARU. A tsunami apparently was initiated by this explosion.

On September 25, there were only three groups of explosions of moderate intensity each, lasting about 1 minute. Those at 1316 and 1823 were apparently seen by the NISSHO MARU which reported explosions at about 1330 and 1830. Inasmuch as this ship reported the eruptions only to the nearest half hour, the correlation is satisfactory.

On September 26, a moderate explosion occurred at 0104 followed by a strong explosion at 1234. This explosion was observed by the SHIKINE MARU which reported an eruption at 1235. A tsunami associated with this explosion was recorded at Hachijo Island beginning at 1303 giving a travel time of 28 minutes. This explosion marked the end of Myojin's major activity.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SEPTEMBER 1952
Microseism Recorded at Hachijo
0725, First Visual Observation by Myojin Maru
Night Photograph LIFE, 13 Oct 1952, p 129
Tsunami Observed Visually During This Period
Small Explosion Photographed (Minakami)
1600, Daytime Photograph LIFE, 13 Oct 1952, p 129
Main Series of Explosions,
Great Steam Cloud, but No Large Explosions Seen
1500 Approx., Large Explosion Cloud Seen Over Myojin
Fire Pillar Observed Over Myojin
0834, Large Explosion Observed
1312, Large Explosion Observed, LIFE, 13 Oct 1952, p 130
1340, Moderate Explosion Observed
1900, Large Explosion Observed
1000, Probable Arrival of Kaiyo Maru
0540, Large Explosion Observed
1221, Double Explosion which Sank Kaiyo Maru
1330 - 1830, Explosions Reported by Nissho Maru
1235, Large Explosion Observed
JAPANESE STANDARD TIME
UNDERWATER SIGNAL DETECTED AT SOFAR STATIONS
INTERVAL DURING WHICH MANY UNDERWATER SIGNALS WERE RECEIVED
INTERVAL OF WAVE RECORDER OPERATION AT HACHIJO
TSUNAMI AT HACHIJO

FIGURE 2.—MYOJIN EXPLOSIONS ACCORDING TO PACIFIC SOFAR STATION RECORDS
(*See* text for explanation of relative intensity scale.)

### *Volcanic Activity at Myojin Subsequent to September 1952*

This paper is concerned almost wholly with the September 1952 explosions at Myojin, and the transpacific transmission of sound that

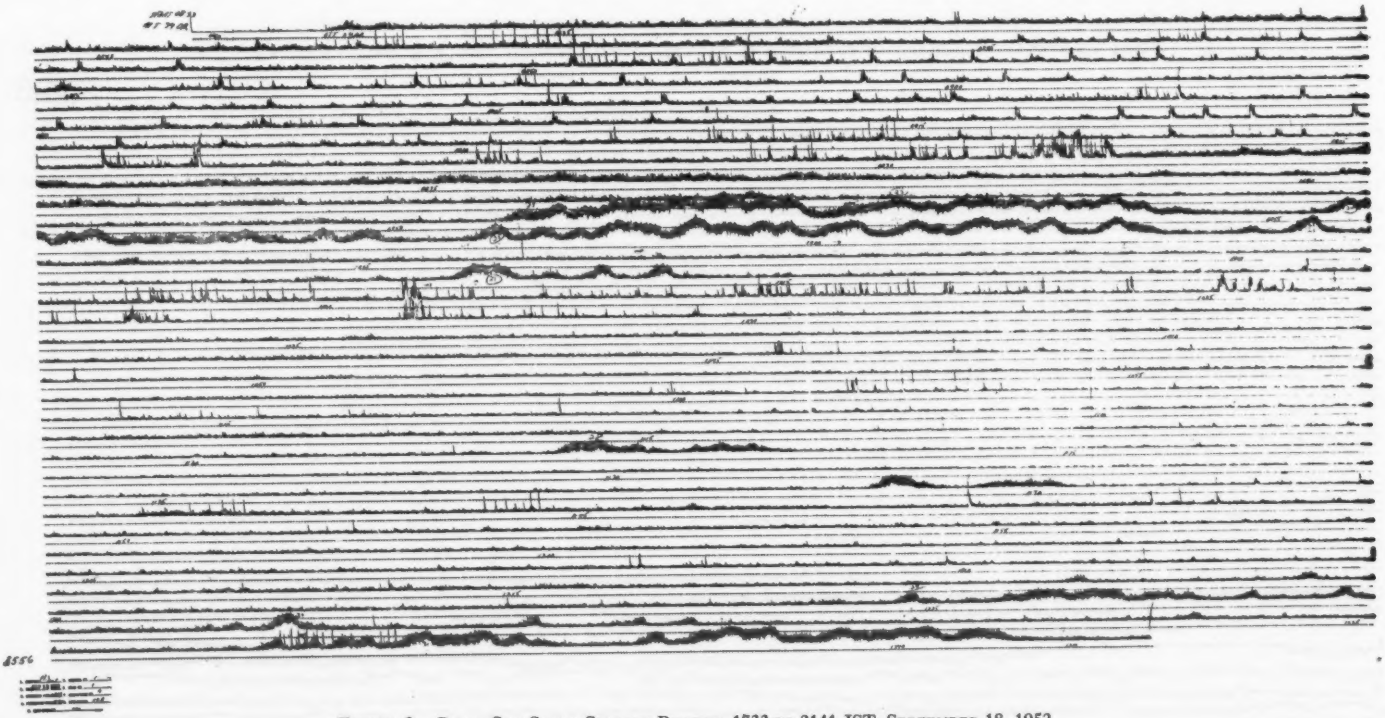

FIGURE 3.—POINT SUR SOFAR STATION RECORD, 1733 TO 2141 JST, SEPTEMBER 18, 1952

(Times written on record are GCT's.) One-second timing divisions appear beneath each trace. Each horizontal line marks a 7½ minute interval.

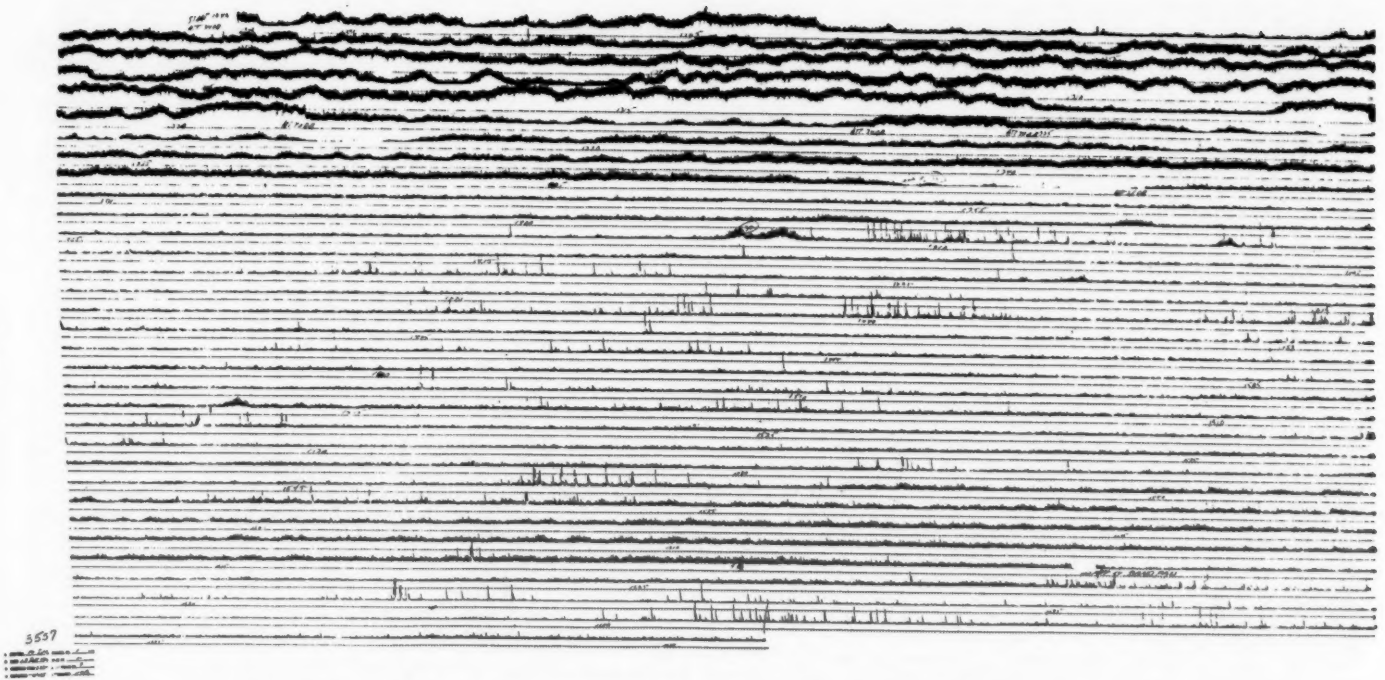

FIGURE 4.—POINT SUR SOFAR STATION RECORD, 2142 JST, SEPTEMBER 18 TO 0148 JST, SEPTEMBER 19, 1952
(Times written on record are GCT's.) One-second timing divisions appear beneath each trace.

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resulted from them. Intermittent activity has continued at Myojin, however, and even at the present writing (May 1953) the eruption that began last September is continuing. It seems worth while to describe briefly the volcanic activity subsequent to September 1952.

A period of inactivity followed the big explosion at about noon on 26 September. Fishing boats in the vicinity did not report any activity, and no explosions were recorded at the Sofar stations. Then the patrol boat MUROTO reported Myojin to be in eruption during 0545 to 0800 on 3 October. No signals were detected at the Sofar stations for this interval, but signals were received corresponding to origin times at Myojin of 0248 and 0531. The latter of these was a strong signal. It may be that the MUROTO arrived on the scene too late to observe these eruptions, and the eruptions she did observe were not strong enough to be detected by the distant Sofar stations.

On 9 December a fishing boat radioed that a new triangular-shaped island approximately 150 feet high was present. An airplane visited the vicinity on 27 December and confirmed the presence of Myojin Island No. 2. When next visited by an aircraft on 8 February 1953, the island had grown to a height of 300 feet and a length of 700 feet (Pl. 4, fig. 1). The northern part of the island consisted of a spikelike pillar, and the southern portion of a dome-shaped mass. The spike portion of the island was clearly a Pelée spine, formed by a hardened plug of lava being slowly ejected from the throat of the volcano.

Like its predecessor, Myojin Island No. 2 was not destined for survival. On the night of 9 March 1953 the fishing boat KANAO MARU reported:

> "great sparks rose into the sky 60 miles to the south of our position. We thought they were flashes of lightning at first, but the phenomenon continued until dawn. Then we could see Myojin belching black smoke at intervals of 30 minutes and a steam column rising to a height of 12,000 to 15,000 feet."

The next morning Hachijo Island was swept by 13 tsunamis, beginning at 0730. These were clearly related to an explosion at Myojin at 0700. This explosion was not detected by the Sofar stations, probably because the equipment had been temporarily modified for other purposes; all the low-frequency acoustic energy was being rejected by the use of a filter. An airplane visited Myojin No. 2 the afternoon of 10 March, but the island had disappeared, and only a patch of discolored water remained to mark the spot where the island had formerly been.

On 18 March several explosions were seen by fishing boats, and during April and May fishing boats and air observers reported continued moderate activity resulting in the formation of a new island (Pl. 4, fig. 2).

### *Destruction of* KAIYO MARU NO. 5

On 23 September, the ill-fated KAIYO MARU No. 5 of the Japanese Maritime Safety Agency departed from Tokyo to investigate the Myojin eruption. The last radio contact with her was on the night of September 23. A few days later several pieces of shattered wreckage were recovered, indicating that she had been lost with her crew of 22, plus 9 scientists including the leader of the expedition, Dr. R. Tayama, a well-known authority on marine geology. Fragments of volcanic rock imbedded in cork and wood showed that the KAIYO MARU No. 5 was destroyed by being enveloped in an explosion cloud. She probably was shattered by the force of the explosion, and possibly was capsized by a tsunami as well.

Inasmuch as dead reckoning would place this ship at Myojin at about 1000 on September 23, it is quite certain that the double explosion at 0539 and 0552 did not destroy her. According to the Sofar data, the only explosion between 0552 and one the following day at 0618 occurred at 1221. This explosion, therefore, must have been the one that blew up the KAIYO MARU No. 5. The large, 1.4-m. tsunami detected at Hachijo beginning at 1253, and hence presumed to originate at Myojin at 1225, confirms this explosion and indicates that it had considerable intensity. From the positions where wreckage was recovered, and by calculating the probable wind drift and current set, it appears that the ship was destroyed sometime in the middle of the morning on 24 September (E. Nakano, personal communication). Since this type of calculation has a probable error of several hours, it is not inconsistent with the other data.

It can be assumed, therefore, that Myojin volcano was in a quiet, dormant state such as it was when the aircraft visited it at noon on 22 September. The KAIYO MARU No. 5 must have considered it safe to approach the reef closely only to be caught by an unexpected and intense explosion.

Murauchi (1952) estimated that the energy of the 0834 eruption of 23 September (Pl. 2) was $10^{18}$ ergs. This is about 1/1000 of the energy released by 20,000 tons of T.N.T.—the reported energy of the Hiroshima type of A-bomb. A conservative computation based on the Sofar data during the 33 minutes of greatest activity, 2007 to 2040 on 18 September, gives a minimum value of $10^{16}$ ergs for the acoustic energy released to the water in the 10–500 cycle per second band. This energy would of course represent only a very small fraction of the total energy of the explosion during that period.

## FUTURE POSSIBILITIES

Inasmuch as the Pacific Basin is considered a volcanic province, interest should be attached to installations similar to those of Sofar stations as a means of monitoring for submarine volcanic eruptions. The signals shown on Figures 3 and 4 are unusual and distinctive, and, if similar signals are received in the future, it could reasonably be supposed that a volcano is erupting somewhere within the reception limits of the station. If three stations received the signals, the eruption could be located with considerable precision.

H. W. Menard (unpub. information) has shown that there are more than 500 known seamounts in the North Pacific Ocean and perhaps several times as many unknown seamounts, most of which are probably of volcanic origin. There may be many deep-sea eruptions for each one which occurs at or near the surface. Inasmuch as deep-sea eruptions have never been reported, they probably do not yield the usual criteria used in identifying shallow submarine eruptions, such as discolored water, the formation of pumice, and the presence of dead, floating fish.

Sofar-type stations may prove useful in detecting deep-sea eruptions even though Pacific Basin volcanoes are typically of the low-explosion Hawaiian type and, more important, the high hydrostatic pressures inhibit explosions. In contrast to high explosives such as T.N.T., which generate pressures up to 50,000 atmospheres (Cole, 1948, p. 3), volcanoes generate

PLATE 1.—MYOJIN AND FUJI VOLCANIC ZONE

REGIONAL SETTING

Open circles indicate active volcanoes along Fugi volcanic zone. Myojin marked by circle with cross; other inactive volcanoes marked with a cross.

One inch equals 115 nautical miles (adapted from Japanese Hydrographic Office Chart 6901).

PLATE 2.—EXPLOSION OF MYOJIN VOLCANO AT 0834 ON SEPTEMBER 23, 1952

All photographs taken by Sugano, of Asahi Press, from SHIN'YO MARU at distance of 5 miles.

FIGURE 1.—TYPICAL INITIAL FORM OF UNDERSEA EXPLOSION OF MYOJIN

Cloud consists of steam and volcanic ash, rocks, gas. Volcanic debris mixed with steam and gas gives cloud black color. Explosion shown is a few seconds old; cloud estimated 1500 feet high and 3300 feet wide.

FIGURE 2.—TWO AND ONE-HALF MINUTES AFTER EXPLOSION

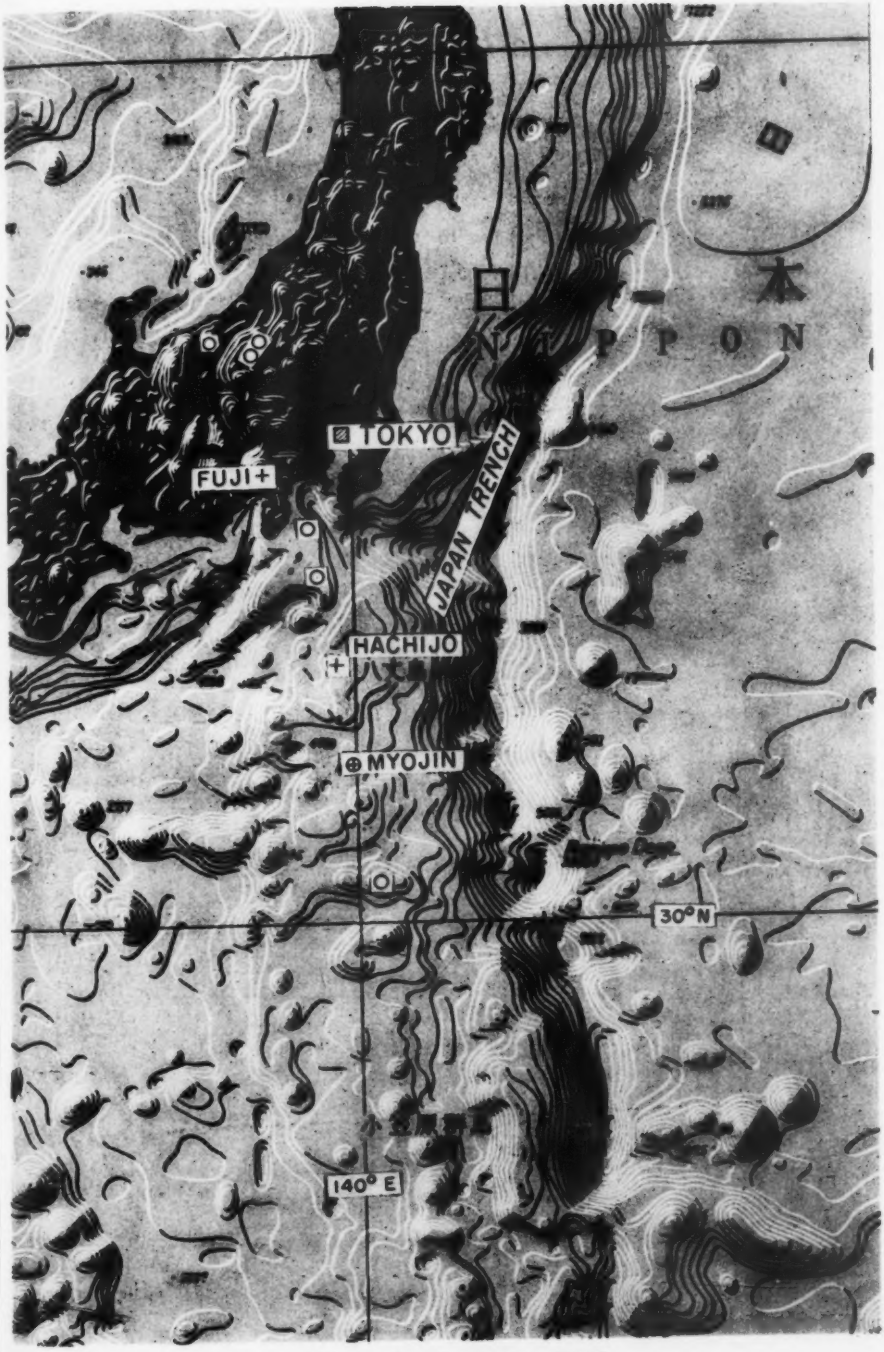
Cloud now 2500 feet high and 6000 feet across its base. Laden with debris, cloud has squashed down on sea and appears to boil outward. Black cloud in left center background apparently marks fresh explosion.

FIGURE 3.—SIX MINUTES AFTER EXPLOSION BEGAN CLOUD HAS COMPLETELY CHANGED ITS FORM

With force of initial outward and upward blast spent, and with debris settled out, surface winds have rushed in from all directions and lifted steam cloud off surface of sea. Explosion apparently has unroofed a large chamber of lava, because steam is being fed into the mushroom cloud. The cloud now 5000 feet across base and 6000 feet high.

FIGURE 4.—EIGHT MINUTES AFTER EXPLOSION BEGAN

Cloud has lifted to about 13,000 feet. Steam cloud will shortly break away from base, drift off, and dissipate.




MYOJIN AND FUJI VOLCANIC ZONE

FIGURE 1

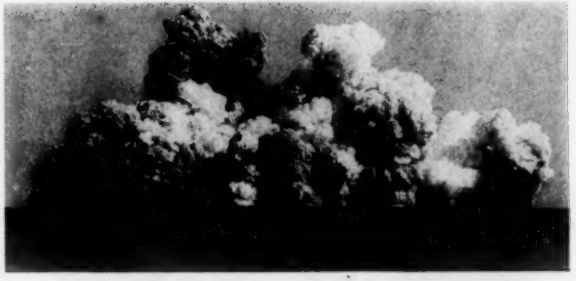


FIGURE 2

FIGURE 3

FIGURE 4

MYOJIN VOLCANO EXPLOSION

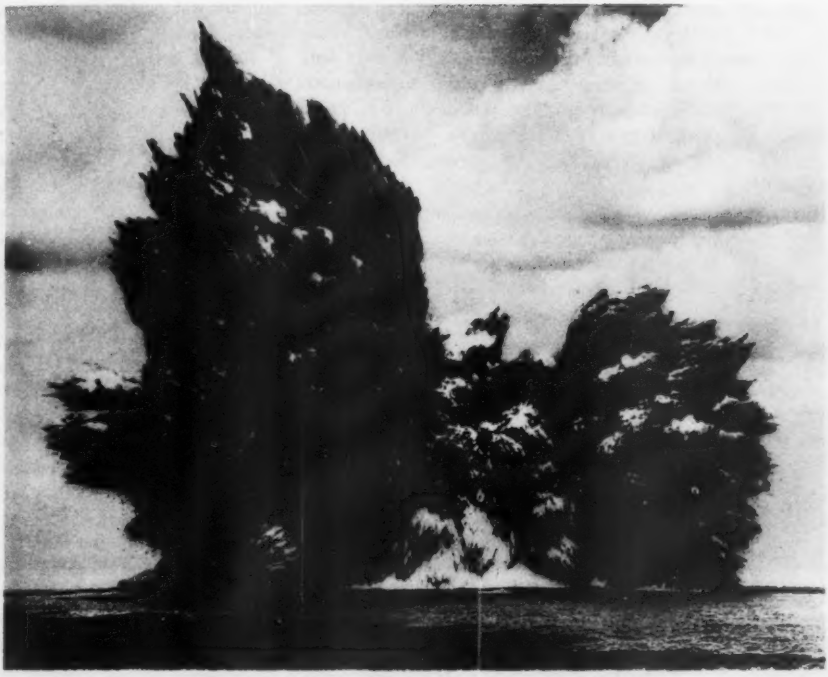


FIGURE 1

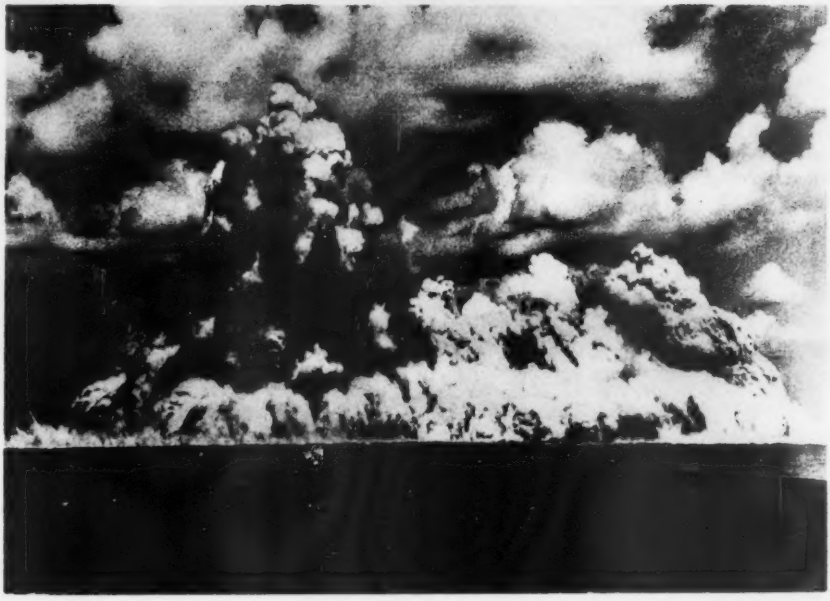


FIGURE 2

EXPLOSIONS

MYOJIN VOLCANO EXPLOSION

FIGURE 1

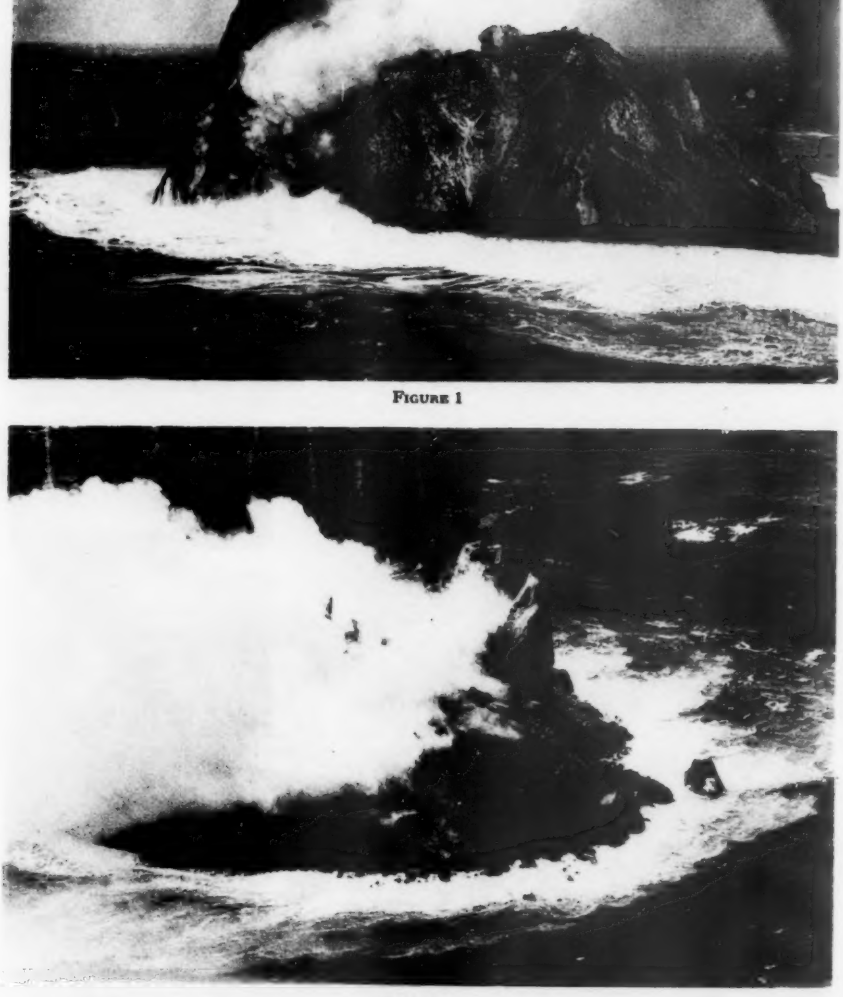


FIGURE 2

LATER MYOJIN ISLANDS

pressures of only a few hundred atmospheres. T. Minakami (personal communication) believes the pressures related to the Myojin eruption were approximately 200 atmospheres. A hydrostatic pressure of this amount is attained at a depth of about 1000 fathoms. However, the greatest explosion of Asama volcano during the 1935–1938 activity had an energy of $1.7 \times 10^{20}$ ergs and 567 atmospheres of pressure at the instant of explosion (Minakami, in press). This pressure is equivalent to that at a depth of 3100 fathoms. It seems then that volcanism on the top of seamounts, and even at the bottom of the ocean, may produce explosions which could be detected by the Sofar system.

The question of the correct identification of such signals is another matter, however. Many of the signals received from the Myojin eruption were not different enough from some other types of underwater signals to be readily distinguishable. T-phases from earthquakes have features in common with some of the Myojin signals, and the weaker Myojin signals resembled Sofar signals originating in high northern latitudes—*i.e.*, in the Gulf of Alaska and near the Aleutians. In the case of small T-phases, however, the sound energy is concentrated in such a low-frequency band that the signals are frequently inaudible over the station loudspeaker system. This may distinguish such signals from those originating from volcanic activity, for the latter were audible over the stations' loudspeakers.

The Sofar station at Kaneohe on Oahu frequently receives signals similar to some of the Myojin ones, but their sources are still undetermined since they have not been correlated with any reported seismic or explosive disturbances. They may be associated with otherwise undetected underground or undersea rumblings in the Hawaiian area, a known volcanic region. These signals, though, are usually inaudible at the station and are thus similar to known T-phases of small magnitude.

The writers were unable to correlate any signals at Sofar stations with the subaerial eruption of Boqueron Crater on San Benedicto Island, off the coast of Mexico, during the summer of 1952. Many unidentified signals were received at the Kaneohe station during the period of eruption, and some of these may have been caused by the volcano. On the few occasions when eruption times were known, however, no signals were discernible. The observed eruptions may have been of a type which did not put much energy into the water, or unknown submerged structures between

PLATE 3.—EXPLOSIONS OF 1312 AND 1340

FIGURE 1.—EXPLOSION OF 1312 ON 23 SEPTEMBER AS SEEN FROM SHIN'YO MARU 1 MILE AWAY

This remarkable photograph, taken with telephoto lens shows 1312 explosion only few seconds old. Large volcanic rocks, hurled outward by force of explosion, can be seen around periphery of debris-laden, black explosion cloud. This explosion not heard aboard ship, although it and hundreds of other explosions were readily detected by Pacific Sofar stations 8600 kilometers away. Photograph by Sugano of the Asahi Press.

FIGURE 2.—EXPLOSION OF 1342 ON 23 SEPTEMBER AS SEEN FROM SHIN'YO MARU 1 MILE AWAY

Remarkably enough, this explosion, although seemingly similar to the others, was the only one reportedly heard on board ship by any observers during entire period of eruption. Photograph by Sugano of the Asahi Press.

PLATE 4.—MYOJIN ISLANDS NO. 2 AND 3 FORMED SUBSEQUENT TO SEPTEMBER 1952 ERUPTION WHICH FORMED AND DESTROYED FIRST ISLAND

FIGURE 1.—AERIAL PHOTOGRAPH OF MYOJIN ISLAND NO. 2 ON FEBRUARY 8, 1953

Island first discovered in December 1952, and destroyed by explosions on March 9 and 10, 1953. On February 1 estimated to be 300 feet high and 700 feet long by observers aboard the UMITAKA MARU. At least the spike-shaped far end of the island is Peléen type. Yomiuri Press photo.

FIGURE 2.—AERIAL PHOTOGRAPH OF MYOJIN ISLAND NO. 3 AS IT APPEARED ON APRIL 14, 1953

Like previous island its form suggests that it has been formed by ejection of lava plug rather than by the extrusion of molten lava. U. S. Air Force photograph.

San Benedicto Island and Kaneohe may prevent sound transmission between those points.

The writers have also been unable to identify Sofar signals which could be related to the 1952 Didacas Rocks eruption off the shelf north of Luzon in the Philippines. However, the geographical location in relation to the Sofar stations, and the origin of the eruption on a shallow shelf, were unfavorable for the transmission of underwater sound signals to the west coast of the United States.

However, these pessimistic observations should not overshadow the long-range potentialities of the work. Detection of underwater signals originating at distant submarine volcanoes is clearly possible. The immediate identification of the majority of such signals cannot, at the present time, be made unequivocally. It is entirely possible, however, that further study will reveal characteristics peculiar to such signals and thus make identification simpler. If so, Sofar stations, or similar installations, may prove of great value to the study of submarine volcanic action.

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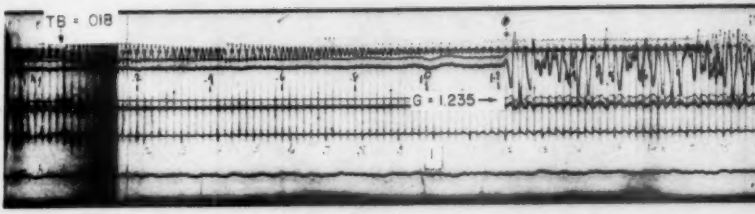
Manuscript Received by the Secretary of the Society, October 8, 1953.

Publication Authorized by Department of Defense, Washington, D. C.

U.S. Navy Electronics Laboratory, Professional Paper Number 32.

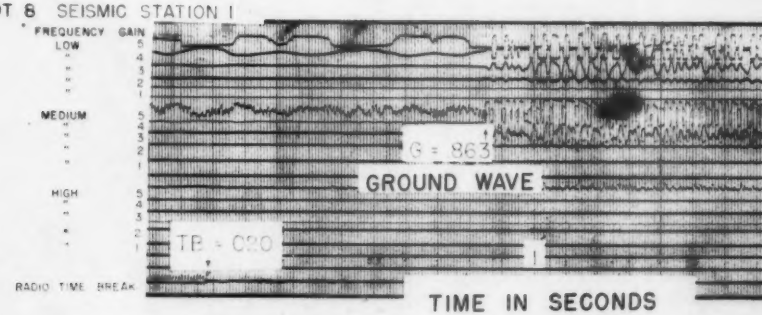
*RELIANCE*

SHOT 850 SEISMIC STATION 36


RADIO TIME BREAK
MARK I HIGH GAIN LOW FREQUENCY
MARK I LOW GAIN LOW FREQUENCY
MARK I LOW GAIN HIGH FREQUENCY
MARK I HIGH GAIN HIGH FREQUENCY
TB = 018
G = 1.235

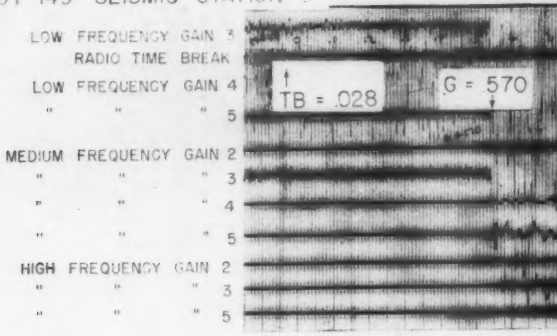
*RETRIEVER*

SHOT 8 SEISMIC STATION 1




*ROCKET*

SHOT 149 SEISMIC STATION 8

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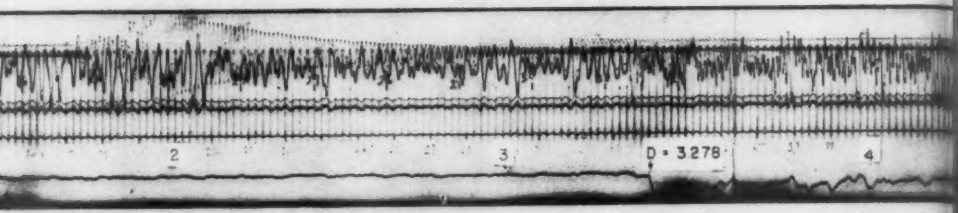


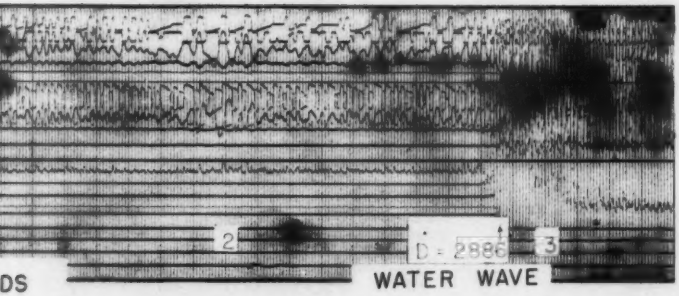


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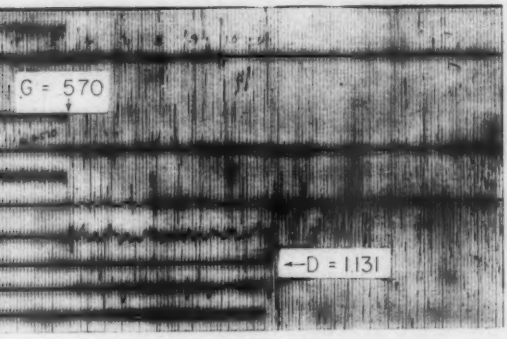


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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 65, PP. 957–970, 14 FIGS., 1 PL. OCTOBER 1954

# GEOPHYSICAL INVESTIGATIONS IN THE EMERGED AND SUBMERGED ATLANTIC COASTAL PLAIN

## PART IX, GULF OF MAINE

BY CHARLES L. DRAKE, J. LAMAR WORZEL, AND WALTER C. BECKMANN

### ABSTRACT

Seismic-refraction measurements were made in the Gulf of Maine in 1948 and 1951 as a continuation of the program of geophysical exploration of the continental margins. Sections from Portland, Maine, to the northwest edge of Georges Bank, from Matinicus Rock, Maine, to Cultivator Shoal, and from Cape Ann, Mass., to Yarmouth, Nova Scotia, were observed.

Sediments (with velocities of 5030 to 6780 ft/sec) varied in thickness from 0 to 1020 feet. North and east of Cashes Ledge consolidated sediments (with velocities of 12,000 to 13,000 ft/sec) were detected up to 1620 feet thick. These are tentatively identified as Triassic and possibly represent an extension of the Fundy Basin. Basement rocks (with velocities of 15,000 to 18,000 ft/sec) thicken under New England and form a troughlike feature off Nova Scotia. Remarkably uniform subbasement rocks (with velocities of 19,000 to 20,000 ft/sec) underlie the Gulf of Maine.

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### INTRODUCTION

The seismic-refraction measurements upon which this paper is based were obtained during the field seasons of 1948 and 1951 by the Lamont Geological Observatory group. Fifteen unreversed profiles were observed in 1948 along a line leading south from Portland as a part of a longer profile extending into deep water. Nine reversed profiles were made in 1951 along two lines: one from Gloucester to Yarmouth, Nova Scotia, and one south from Matinicus Rock to Georges Bank. In addition to these data, reference is made to results obtained by Katz, Edwards, and Press (1953, p. 249–252), using land seismometers to record shots in the Gulf of Maine.

### ACKNOWLEDGMENTS

Investigations were carried out by personnel of the Lamont Observatory under contract N6

onr 27113 with the Office of Naval Research and NObsr 43355 with the Bureau of Ships of the U. S. Navy. Explosives were furnished by the Bureau of Ordnance, U. S. Navy.

The 1948 work was done aboard vessels of the Woods Hole Oceanographic Institution, sufficient to cover the distances involved in the program, CARYN also served as a tanker, refueling these vessels at sea.

The recording camera used aboard RETRIEVER was furnished by the Atlantic Refining Company. C. Bentley, J. Northrop, E. Smith,

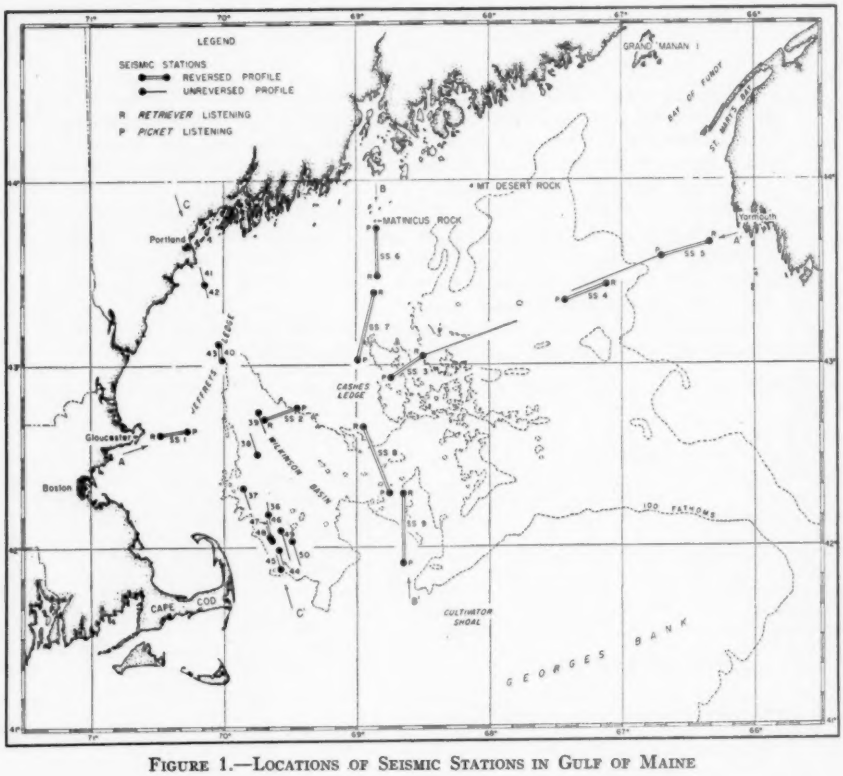



FIGURE 1.—LOCATIONS OF SEISMIC STATIONS IN GULF OF MAINE

LIDA AND DICK doing the shooting and RELIANCE recording the shots. G. R. Hamilton, R. S. Edwards, E. T. Miller, T. Madden, J. Northrop, W. Kelly, and D. H. Shurbet participated in the field work.

The recording of the data in the 1951 program was carried out aboard two small craft, a 42-foot Motor Torpedo Retriever, and a 38-foot Picket Boat, supplied to Lamont Observatory as Government-Furnished Equipment. The shooting was done from R/V CARYN of the Woods Hole Oceanographic Institution. Since the cruising range of the small craft was in-

D. Warren, F. Diefenbacher, C. K. Ferns, B. Meyerson, L. Johnson, and D. G. Foster, Jr. participated in the field work.

## LOCATION OF STATIONS

The program of refraction measurements in 1948 was a continuation of the studies of the emerged and submerged Atlantic Coastal Plain being conducted by Lamont Geological Observatory. Since the purpose of this work was to study the configuration of the basement surface and the nature of the sediments above,

the profiles are relatively short, averaging 7 miles (Fig. 1). Since they are closely spaced, they give detail of the local variations in the unconsolidated layer but are limited in depth of penetration. The majority were shot as single profiles but were spaced in such a manner that most can be reversed with adjacent profiles.

The 1951 program was initiated as a result of examination of the submarine gravity measurements made aboard USS TUSK. These showed a strong gravity high in the Gulf of Maine area. The program was set up to investigate the possibility that the deeper crustal layers were closer to the surface than measurements usually indicate for continental regions. Thus the profiles are long, resulting in a loss of detail in the upper layer, but giving better determinations of velocities in the lower layers and making it possible to search for deeper discontinuities. In both sets of data, the positions of recording stations were determined by Loran, if land was not visible, and by visual bearings on landmarks whenever possible. Owing to the configuration of the Loran network in the area, the accuracy of positioning parallel to the Maine coast cannot be as precise as that normal to the coast. Thus, for Loran fixes, accuracy of only 2–4 miles can be claimed for the former, while the probable error is only 1 mile for the latter. In the case of fixes by visual bearings, probable error is less than half a mile.

## METHODS OF INVESTIGATION AND INTERPRETATION

With some minor exceptions, the methods used in this work were those described by Officer and Wuenschel (1951) for the deep-sea refraction measurements. The 1948 work was done in the usual manner, one vessel shooting, the other recording. For the 1951 work the two small craft stationed themselves at the ends of a profile, and CARYN shot a single line between them, thus reversing the profile in one pass. There is no saving in powder using this method since, except for small close shots at each end to determine the velocity and intercept of the superficial layer, all the charges must be relatively large to insure that both vessels pick up ground waves. There is, however, a significant saving in the time necessary to complete a reversed profile, a factor of some importance in this case because of uncertainities of the weather and the small size of the boats.

It is appropriate to mention here that still a third technique was used by Katz in 1949 (Katz, *et al.*, 1953, p. 249–252). Here recording stations were established at two stations in Maine and one in Nova Scotia, to receive shots fired on an absolute time schedule by USS MENTOR in the Gulf of Maine. The first part of the profile, from Portland to Matinicus, could be reversed, while the latter part, continuing toward Yarmouth could not be reversed owing to mechanical failures which caused MENTOR to turn back before completion of the experiment.

Plate 1 illustrates a sample record from 1948 at the top, and records from the two vessels recording in 1951 below. The traces are marked as to gain and frequency response, and the arrivals labeled.

In all cases, the charges were fired electrically, and the switch which provided the firing current also caused a zero time mark to be transmitted to the recording vessels. In order to find the delay in the firing circuit, caps were fired 5 feet from the hydrophones of the recording vessels at frequent intervals. The correction was negligible.

Timing was accomplished by means of tuning forks or fork-controlled synchronous motors. In 1948, the fork was checked against 60-cycle commercial power whenever in port. Assuming the frequency of the commercial power to be accurate, the fork showed a gain of 0.050 sec/sec. In 1951, the units were checked against WWV and found to have negligible rates.

In the majority of cases, the shots were not on the bottom. The depth of shot, in this event, was determined from the bubble-pulse intervals. As noted by Ewing, (Ewing *et al.*, 1946, p. 913–916) the frequency of oscillation of the gas bubble resulting from an underwater explosion is a function of charge size and depth. The hydrophones were kept at constant depths, and a suitable correction applied.

The velocity of sound in the water was determined from cumulative data furnished by the Woods Hole Oceanographic Institution. The horizontal velocity varied less than 1 per cent from 4880 ft/sec, the vertical less than 1

per cent from 4380 ft/sec. The method of interpretation is that employed in Part III of this series (Ewing *et al.*, 1938, p. 262–267). While it does not seem advisable to repeat the derivations, it is desirable to restate the basic

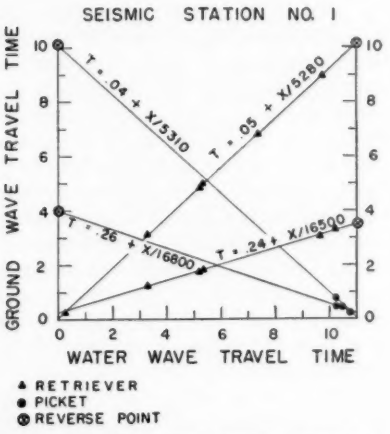



FIGURE 2.—TRAVEL-TIME CURVES, PROFILE 1

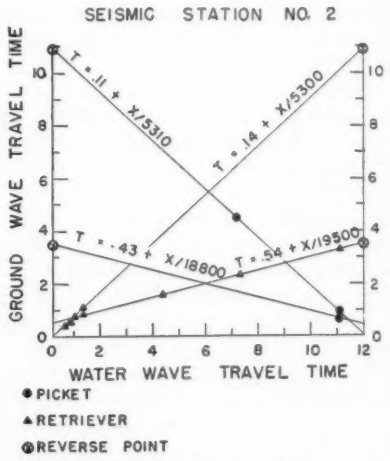



FIGURE 3.—TRAVEL-TIME CURVES, PROFILE 2

assumptions and describe any modifications of the technique which may have been used in this paper.

The interpretations are based on the following assumptions:

(1) Each layer is bounded at top and bottom by planes and transmits seismic waves at a constant velocity.

(2) At the interface between two layers the path of the seismic wave is bent according to Snell's Law.

(3) A wave travelling in any layer with a velocity $V$ and incident upon the surface of the layer at an angle, $\alpha$, with the normal has an apparent velocity $V/Sin\,\alpha$ along the surface.

(4) Any travel time will be unchanged if the positions of the shot point and the receiving point are interchanged. The interchanged points at the two ends of a reversed profile are reverse points.

If one vessel moves away from the other, dropping charges at intervals, a series of points (Figs. 2–13) will be obtained by the stationary vessel which, for any single layer conforming to the above assumptions, will fall on a straight line. If the roles of the two vessels are then reversed, another line will result sloping the opposite way. These slopes will be equal only if the layer is level. If the layer is dipping, the slopes will differ; the lower slope, or higher apparent velocity, will be found when the recording vessel is down dip. In either level or dipping beds, the reverse points should be equal unless the drift of the vessel carries it over changes in the underlying structure. The agreement of the reverse points normally may be taken as an indication of the importance of the drift factor.

Commonly a profile will cover more than one layer. Points identifying a specific layer will occur only over a portion of the total length of the profile. Consistent with the basic assumptions, these segments may be extended to give a reverse point and an intercept. From the intercepts, and from the apparent velocities, the thicknesses, dips, and true velocities may be calculated without difficulty in most cases.

In several of the profiles in this paper points on the reverse line were not found for one of the layers. This may be due to pinching out of the layer near the reverse point, or arrivals from the layer may be masked by earlier arrivals from the other layers. In this paper the former possibility is considered most probable, and the resulting computed velocites agree with velocities in the same layer in adjacent profiles.

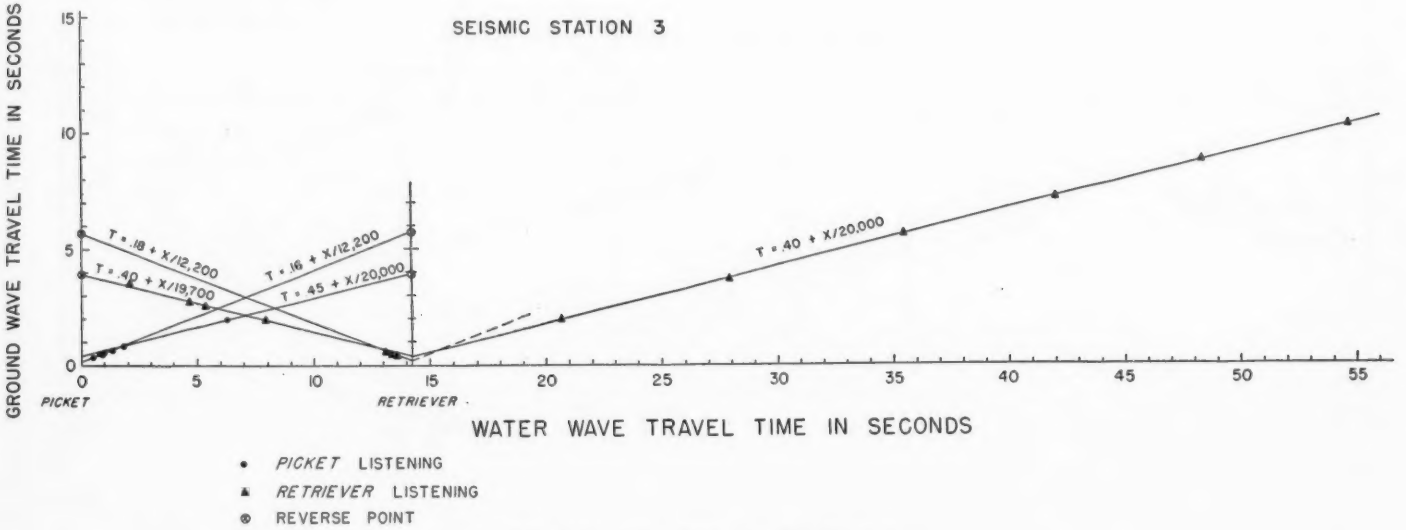



FIGURE 4.—TRAVEL-TIME CURVES, PROFILE 3

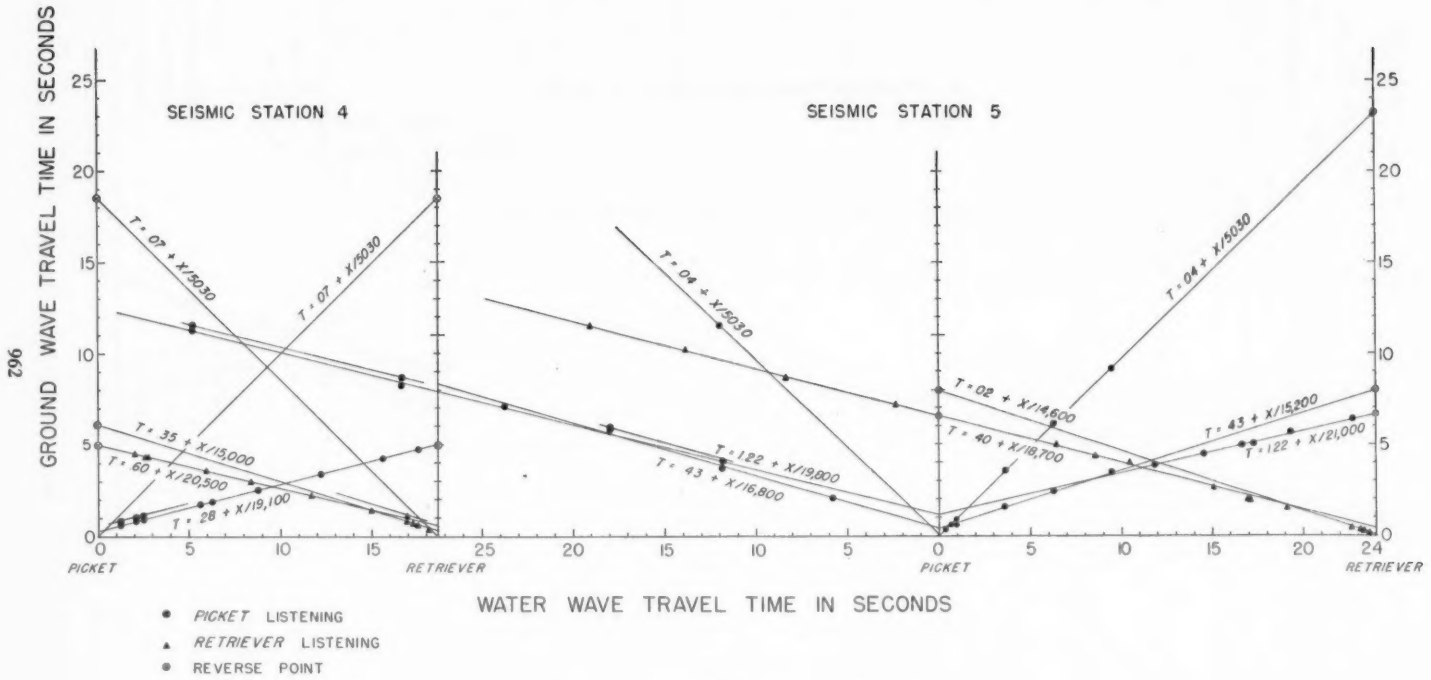
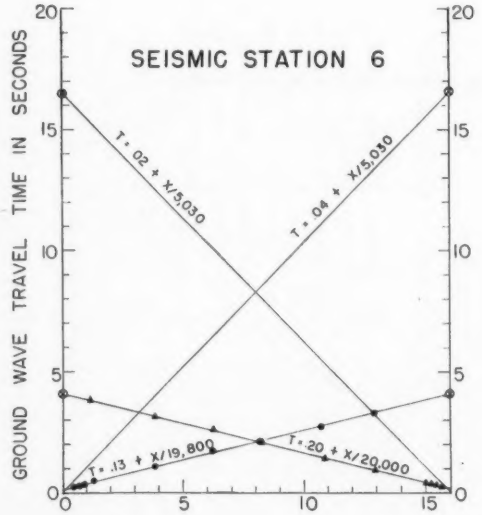
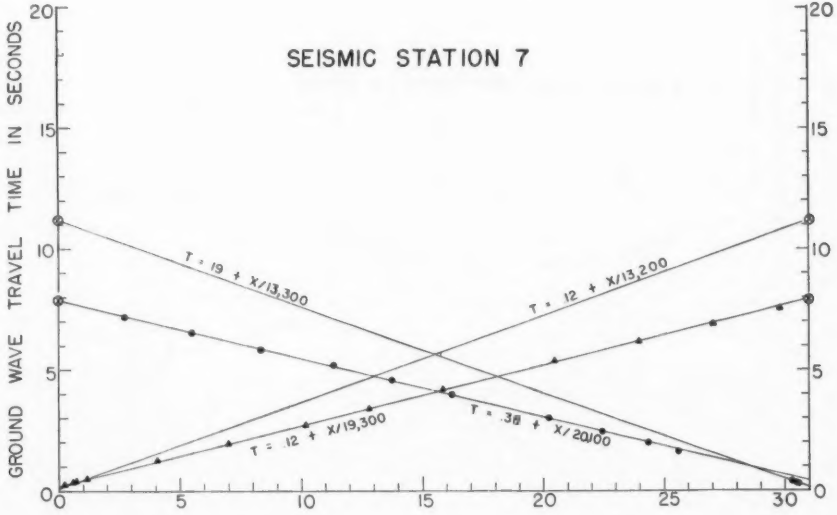



FIGURE 5.—TRAVEL-TIME CURVES, PROFILES 4, 5




• PICKET
▲ RETRIEVER
◉ REVERSE POINT

WATER WAVE TRAVEL TIME IN SECONDS

FIGURE 6.—TRAVEL-TIME CURVES, PROFILE 6

FIGURE 7.—TRAVEL-TIME CURVES, PROFILE 7

SEISMIC STATION 8
SEISMIC STATION 9
T = 20 + X/6780
T = 15 + X/6780
T = 32 + X/19300
T = 37 + X/19500
T = 23 + X/6780
T = 18 + X/6780
T = 48 + X/19800
T = 30 + X/19500
GROUND WAVE TRAVEL TIME IN SECONDS
WATER WAVE TRAVEL TIME IN SECONDS
• PICKET
▲ RETRIEVER
⊕ REVERSE POINT

FIGURE 8.—TRAVEL-TIME CURVES, PROFILE 8

FIGURE 9.—TRAVEL-TIME CURVES, PROFILE 9

A number of the records from profiles 4 and 5 (Fig. 5) show strong second arrivals which plot parallel to but above the lines of first

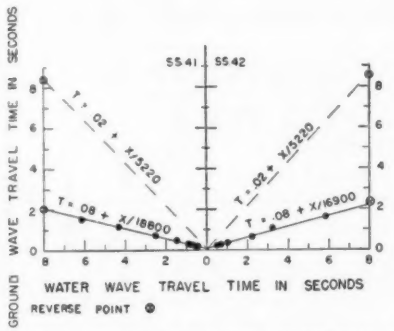

SS 41
SS 42
T = .02 + X/5220
T = .08 + X/18600
T = .02 + X/5220
T = .08 + X/16900
GROUND WAVE TRAVEL TIME IN SECONDS
WATER WAVE TRAVEL TIME IN SECONDS
REVERSE POINT

FIGURE 10.—TRAVEL-TIME CURVES, PROFILES 41, 42

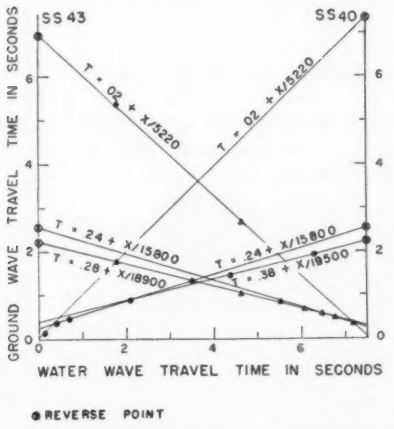

SS 43
SS 40
T = .02 + X/5220
T = .02 + X/5220
T = .24 + X/15800
T = .28 + X/18900
T = .24 + X/15800
T = .38 + X/19500
GROUND WAVE TRAVEL TIME IN SECONDS
WATER WAVE TRAVEL TIME IN SECONDS
REVERSE POINT

FIGURE 11.—TRAVEL-TIME CURVES, PROFILES 43, 40

arrivals. The time separation between these and the first arrivals is equal to twice the time necessary for sound to travel the water depth; hence they are interpreted as arrivals which were reflected once on the bottom and once on the surface before being refracted. This type of arrival has been reported in Part V (Ewing *et al.*, 1950, p. 883) of this series.

## TRAVEL-TIME DATA AND RESULTS

Travel-time curves for the 1948 and the 1951 data are presented in Figures 2–13. For those profiles in which no points were observed on the unconsolidated sediment line, the velocity found for this layer in an adjacent profile was used with the water depth as determined by echo sounder to find the sediment thickness. In profiles 3 and 7 (Figs. 4, 7) this computation

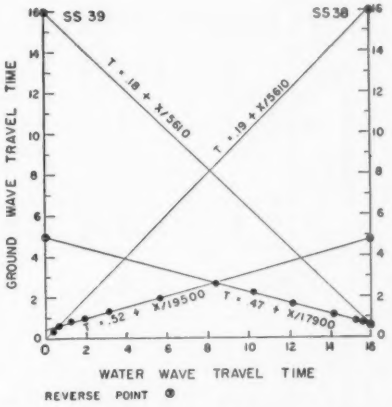



FIGURE 12.—TRAVEL-TIME CURVES, PROFILES 38, 39

gave a thickness of zero feet for this layer. This does not necessarily indicate absence of sediment, but rather that the sedimentary layer is thinner than the minimum detected by the seismic method used. No data were observed for the basement layer on the southwest end of profile 4 (Fig. 5). Here it was assumed that the bed thinned to zero. The velocity computed on the basis of this assumption agrees well with that found in profile 5 (Fig. 5). A similar assumption was made for the north end of profile 7 (Fig. 7).

A summary of the data and the results is presented in Table 1. The maximum dip found in the entire survey is slightly over 2°. Since this is small, the consequences of drift of the recording boats, a quantity difficult to ascertain, are relatively small.

There is considerable variation in the thickness of the unconsolidated sediments. They seem to be absent in the middle of the Gulf but are found along the present shore line in varying thicknesses, and thicken appreciably toward Georges Bank; the south end of profile 9 (Fig. 1) shows a thickness in excess of 1000 feet. The velocity in these sediments varies

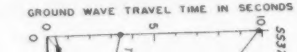
TABLE 1.— SUMMARY OF SEISMIC REFRACTION DATA IN THE GULF OF MAINE
Summary of seismic-refraction data in Gulf of Maine.

| No. | Water | Unconsolidated sediment | Consolidated sediment | Basement | Sub-basement | Slopes of Layers | | | | Velocities (ft/sec) | | | | Thicknesses (ft) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | $W_1$ | $W_2$ | $W_3$ | $W_4$ | $V_1$ | $V_2$ | $V_3$ | $V_4$ | $h_1$ | $h_2$ | $h_3$ | $h_4$ |
| IR | x/4880 | T=.05+x/5280 | ..... | T=.24+x/16500 | ..... | −23′ | 18′ | ..... | ..... | 5300 | ..... | 16600 | ..... | 330′ | 310′ | ..... | ..... |
| IP | x/4880 | T=.04+x/5310 | ..... | T=.26+x/16800 | ..... | | | | | | | | | 440′ | 480′ | ..... | ..... |
| 2R | x/4880 | T=.14+x/5300 | ..... | ..... | T=.54+x/19500 | −8′ | 9′ | ..... | ..... | 5300 | ..... | ..... | 19200 | 860′ | 550′ | ..... | ..... |
| 2P | x/4880 | T=.11+x/5310 | | ..... | T=.43+x/18800 | | | | | | | | | 760′ | 450′ | ..... | ..... |
| 3P | x/4880 | ..... | T=.16+x/12200 | ..... | T=.45+x/20100 | 0′ | ..... | 23′ | ..... | .... | 12200 | ..... | 19900 | 600′ | ..... | 1620′ | ..... |
| 3R | x/4880 | ..... | T=.18+x/12200 | ..... | T=.40+x/19700 | | | | | | | | | 590′ | ..... | 1300′ | ..... |
| 4P | x/4880 | T=.07+x/5030 | ..... | T=.28+x/15000 | T=.28+x/19100 | −2′ | 1′ | ..... | −2°15′ | 5030 | ..... | 15000 | 19800 | 680′ | 20′ | ..... | 0′ |
| 4R | x/4880 | T=.07+x/5030 | ..... | T=.35+x/15000 | T=.60+x/20500 | | | | | | | | | 750′ | 150′ | ..... | 3000′ |
| 5P | x/4880 | T=.04+x/5030 | ..... | T=.43+x/15200 | T=1.22+x/21100 | 7′ | 21′2 | ..... | 2°01′ | 5030 | ..... | 15000 | 19500 | 410′ | 710′ | ..... | 9820′ |
| 5R | x/4880 | ..... | ..... | T=.02+x/14700 | T=.40+x/18700 | | | | | | | | | 180′ | 0′ | ..... | 3770′ |
| 6P | x/4880 | T=.04+x/5030 | ..... | ..... | T=.13+x/19800 | −9′ | 2′ | ..... | ..... | 5030 | ..... | ..... | 19800 | 180′ | 160′ | ..... | ..... |
| 6R | x/4880 | T=.02+x/5030 | ..... | ..... | T=.20+x/20000 | | | | | | | | | 370′ | 130′ | ..... | ..... |
| 7R | x/4880 | ..... | T=.12+x/13200 | ..... | T=.12+x/19400 | −5′ | ..... | −34′ | ..... | .... | 13200 | ..... | 19700 | 300′ | ..... | 0′ | ..... |
| 7P | x/4880 | ..... | T=.19+x/13300 | ..... | T=.38+x/20100 | | | | | | | | | 480′ | ..... | 1620′ | ..... |
| 8R | x/4880 | T=.15+x/6780 | ..... | ..... | T=.32+x/19300 | −4′ | 0′ | ..... | ..... | 6780 | ..... | ..... | 19400 | 520′ | 400′ | ..... | ..... |
| 8P | x/4880 | T=.20+x/6780 | ..... | ..... | T=.37+x/19500 | | | | | | | | | 700′ | 330′ | ..... | ..... |
| 9R | x/4880 | T=.18+x/6780 | ..... | ..... | T=.30+x/19500 | −2′ | −8′ | ..... | ..... | 6780 | ..... | ..... | 19700 | 610′ | 180′ | ..... | ..... |
| 9P | x/4880 | T=.23+x/6780 | ..... | ..... | T=.48+x/19800 | | | | | | | | | 710′ | 1020′ | ..... | ..... |
| LR41 | x/4880 | T=.02+x/5220 | ..... | T=.08+x/18800 | ..... | 0′(?) | −54′ | ..... | ..... | 5220 | ..... | 18000 | ..... | 160′ | 60′ | ..... | ..... |
| LR42 | x/4880 | T=.02+x/5220 | ..... | T=.08+x/16900 | ..... | | | | | | | | | | | | |
| LR43 | x/4880 | T=.02+x/5220 | ..... | T=.24+x/15800 | T=.28+x/18900 | 0′ | 0′ | ..... | 1°20′ | 5220 | ..... | 15800 | 19400 | 160′ | 480′ | ..... | 1870′ |
| LR40 | x/4880 | T=.02+x/5220 | ..... | T=.24+x/15800 | T=.38+x/19500 | | | | | | | | | 160′ | 490′ | ..... | 620′ |
| LR39 | x/4880 | T=.19+x/5610 | ..... | ..... | T=.52+x/19500 | 2′ | 43′ | ..... | ..... | 5610 | ..... | ..... | 18700 | 940′ | 430′ | ..... | ..... |
| LR38 | x/4880 | T=.18+x/5610 | ..... | ..... | T=.47+x/17900 | | | | | | | | | 900′ | 320′ | ..... | ..... |
| LR37 | x/4880 | T=.17+x/5860 | ..... | ..... | T=.42+x/20400 | 6′ | 20′ | ..... | ..... | 5860 | ..... | ..... | 19800 | 760′ | 240′ | ..... | ..... |
| LR36 | x/4880 | T=.19+x/5860 | ..... | ..... | T=.38+x/19300 | | | | | | | | | 600′ | 240′ | ..... | ..... |
| LR46 | x/4880 | T=.19+x/6730 | ..... | ..... | T=.32+x/20300 | 14′ | 1′ | ..... | ..... | 6730 | ..... | ..... | 19800 | 800′ | 10′ | ..... | ..... |
| LR48 | x/4880 | T=.17+x/6730 | ..... | ..... | T=.32+x/19600 | | | | | | | | | 740′ | 80′ | ..... | ..... |
| LR49 | x/4880 | T=.17+x/6640 | ..... | ..... | T=.32+x/18000 | 3′ | −1°07′ | ..... | ..... | 6640 | ..... | ..... | 19000 | 720′ | 100′ | ..... | ..... |
| LR47 | x/4880 | T=.17+x/6640 | ..... | ..... | T=.41+x/19900 | | | | | | | | | 700′ | 480′ | ..... | ..... |
| LR50 | x/4880 | ..... | ..... | T=.33+x/18100 | | | | | | | | | | | | | |
| LR44 | x/4880 | T=.17+x/6000 | ..... | T=.50+x/18500 | ..... | 5′ | 36′ | ..... | ..... | 6000 | ..... | 18000 | ..... | 750′ | 630′ | ..... | ..... |
| LR45 | x/4880 | T=.15+x/6000 | ..... | T=.32+x/17200 | ..... | | | | | | | | | 670′ | 170′ | ..... | ..... |

*Slopes*
$W_1$ = slope of bottom
$W_2$ = slope of bottom of unconsolidated sediment
$W_3$ = slope of bottom of consolidated sediment
$W_4$ = slope of bottom of basement
Negative slopes are down to North and to East

*Velocities*
$V_1$ = sediment
$V_2$ = consolidated sediment
$V_3$ = basement
$V_4$ = sub basement

*Thicknesses*
$h_1$ = water
$h_2$ = sediment
$h_3$ = consolidated sediment
$h_4$ = basement

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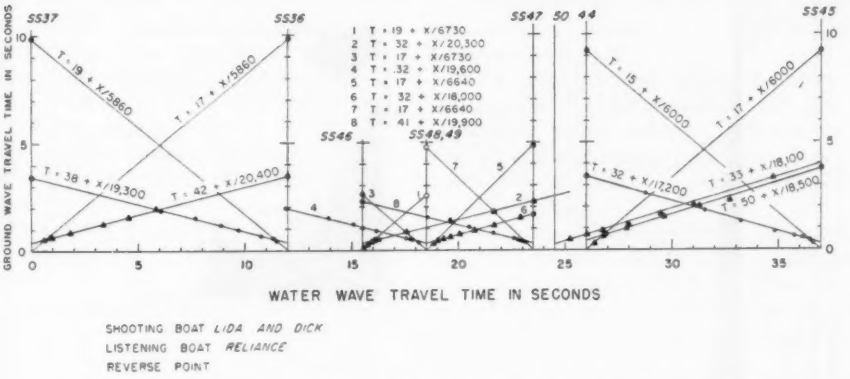
from 5030 ft/sec to 6730 ft/sec with a general trend toward higher velocities approaching Georges Bank.

The velocity in the consolidated sediment layer of profile 7 (Fig. 7) is higher than that with all these values (Fig. 14). An upper layer of 5.13 km/sec was found overlying a lower layer of 5.97 km/sec. Although the lower layer was present over the entire Gulf of Maine, the upper thickens under New England, forms


SS37
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SS48,49
1 T = .19 + X/6730
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3 T = .17 + X/6730
4 T = .32 + X/19,600
5 T = .17 + X/6640
6 T = .32 + X/18,000
7 T = .17 + X/6640
8 T = .41 + X/19,900
T = .19 + X/5860
T = .17 + X/5860
T = .38 + X/19,300
T = .42 + X/20,400
T = .15 + X/6000
T = .17 + X/6000
T = .32 + X/17,200
T = .33 + X/18,100
T = .50 + X/18,500
GROUND WAVE TRAVEL TIME IN SECONDS
WATER WAVE TRAVEL TIME IN SECONDS
SHOOTING BOAT LIDA AND DICK
LISTENING BOAT RELIANCE
REVERSE POINT

FIGURE 13.—TRAVEL-TIME CURVES, PROFILES 37, 36, 46, 48, 49, 47, 50, 44, 45

of profile 3 (Fig. 4) but is not in excess of the limit of error of the determinations.

The velocity variation in the basement layer is to be expected from earlier results (Parts I–VII). The mean velocity in this layer is 16,800 ft/sec (5.13 km/sec). The resultant velocity from profiles 41–42 (Fig. 10) may be in error since these are not truly reversed but are end to end.

The velocities found in the subbasement are remarkably uniform. In spite of the differences between the two sets of data, the maximum variation from the mean value of 19,600 ft/sec (5.97 km/sec) is only 4 per cent and that is on a short profile.

### GEOLOGIC IMPLICATIONS

Leet (1941, p. 326) has given the velocity in the uppermost layer in New England as 6.13 km/sec. Hodgson (1945, p. 15) finds comparable results in Ontario, giving a velocity of 6.15 km/sec. In the work by Katz *et al.* (1953, p. 249) the station recording at Falmouth, Maine, showed an uppermost layer 5.2 km thick with a velocity of 5.34 km/sec overlying a 6.24 km/sec layer.

The present study agrees reasonably well a troughlike feature off Nova Scotia, and is absent over most of the central area. Thus, in the center of the Gulf, the crustal section agrees with those of Leet and Hodgson, while along the borders it is similar to that of Katz.

The mean velocity found in the basement layer compares favorably with the values given by various writers for granite (Leet and Ewing, 1932, p. 164–167; Leet, 1933, p. 375; Gutenberg *et al.*, 1932, p. 214). Although this is a mean velocity, it probably indicates the presence of granite or granitic rocks, and may possibly be correlated with the Paleozoic intrusives of this area. The geologic map of Nova Scotia (1949) shows a greater abundance of these to the south than in the southwest where Section A-A′ meets the coast, but the troughlike feature found off the coast suggests that the intrusives are more abundant off shore in the latter area.

G. H. Chadwick presented a series of cross sections depicting the geologic history of the Gulf of Maine at the meetings of the Geological Society of America in El Paso in 1949 which have been reproduced by Eardley (1951, p. 134). In these sections he showed the Triassic of the Bay of Fundy extending into the Gulf

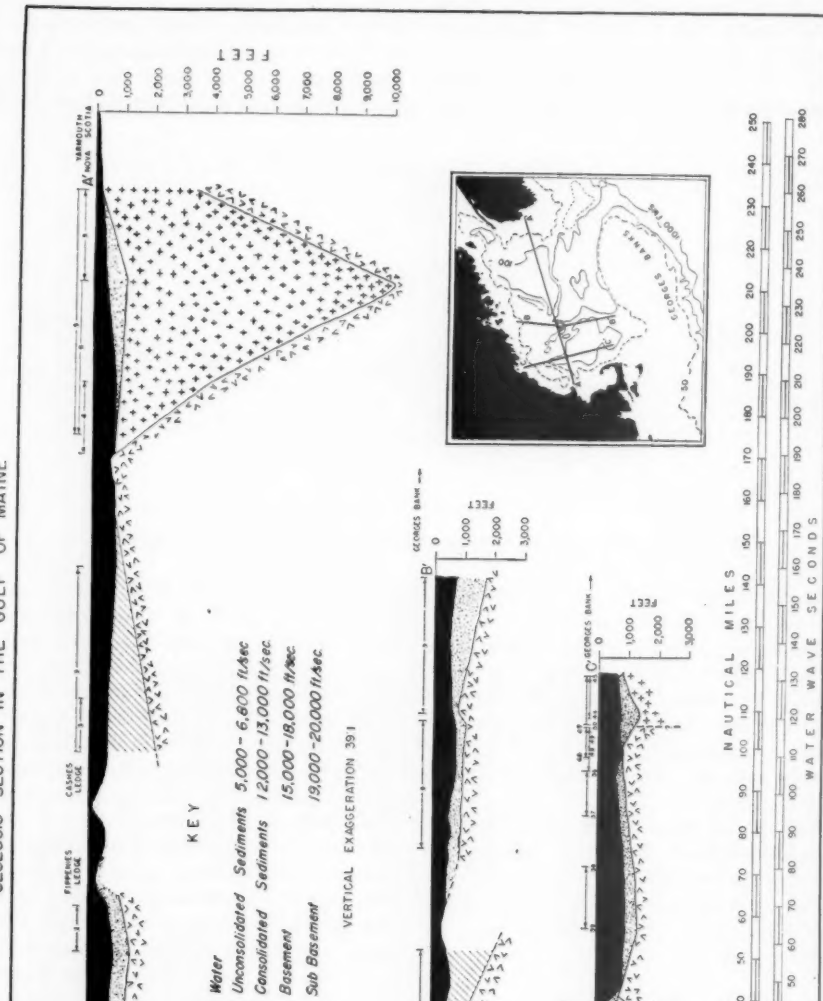


FIGURE 14.—GEOLOGIC CROSS SECTIONS CONSTRUCTED FROM SEISMIC DATA

of Maine with a border fault on the northern side. Johnson (1925, p. 295) on the basis of geomorphological considerations, proposed that the Triassic basin extended as far as Jeffreys Bank. This and the question of a border fault have been debated by Koons (1941; 1942) and Shepard (1930; 1942), the latter claiming glacial action rather than a border fault as the cause of the submarine scarps found here.

The velocity for the consolidated sediment layer found north and east of Cashes Ledge (Fig. 14) agrees with velocities given for Triassic red beds in the "Handbook of Physical Constants", (Birch *et al.*, 1942, p. 96) and that found by Worzel (1951) in the Hudson River under the Palisades diabase. The maximum thickness found for this layer was 1620 feet, which is somewhat thinner than that given by Powers (1916, p. 6) for the Acadian section (3300–6500 feet) but is comparable to the Quaco section, New Brunswick, where it measures 1550 feet. If, then, this layer represents Triassic sediments, it is probably an extension of the Fundy basin. Because of the reconnaissance nature of the data, no conclusions are drawn as to the existence of a boundary fault.

A possible source of error in the thickness of the consolidated sediment may appear if the basalt flows found in the Fundy area extend into this region. If the lower-velocity sediments were topped by a cover of high-velocity basalt, they would not be discovered by the standard refraction method. Thus only that part of the section above the flows would be recorded. (No evidence was found of such a low velocity.)

The wedge of Mesozoic and Cenozoic coastal plain sediments noted in the earlier papers is largely absent from this area. Except for remnants of this wedge, probably somewhat reworked by glacial action and other erosional processes, the majority of the sediments, especially those lining the present coast line, appear recent. It is interesting to note that a number of the topographic features are in this unconsolidated layer and are not due to more competent materials. Jeffreys Ledge, thought by Johnson to be an extension of the Cape Ann granite, does have the granite layer beneath it, but the relief in the area surveyed is in the unconsolidated sediments. It is probable that Fippenies Ledge is similar.

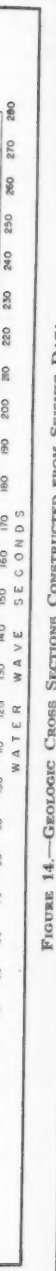


FIGURE 14.—GEOLOGIC CROSS SECTIONS CONSTRUCTED FROM SEISMIC DATA

## CONCLUSIONS

The wedge of coastal plain sediments found south of the Gulf of Maine is largely absent from the Gulf itself. Variable thicknesses of reworked sediments range from 0 to over 1000 feet within the area, while the wedge proper starts to thicken seaward at the inner margin of Georges Bank.

The presence of Triassic sediments confirms the opinions of earlier workers in the area. The western limit of these sediments is in the vicinity of Cashes Ledge. The data are not sufficient to determine the presence or absence of a boundary fault.

Variable seismic velocities in the basement rocks, such as are found here, were reported in the earlier papers of this series. These velocities depend on the nature of the local geology, and in the Gulf of Maine the basement may be best correlated with the Paleozoic intrusives of New England and Nova Scotia. The mean velocity of the basement, 5.13 km/sec, agrees with the value of 5.24 km/sec given by Katz for a station at Falmouth, Maine.

The presence of a subbasement layer with uniform seismic velocity marks an important difference between the Gulf of Maine and the shallow-water areas examined in the earlier papers of this series. This layer may be identified with an upper layer of 6.0–6.3 km/sec found by typical continental seismograph stations in the region.

The nature of the density excess causing the broad positive gravity anomaly was not determined. Using a velocity of 8.0 km/sec for the material below the Mohorovičić discontinuity, a minimum depth for this discontinuity of 15 km may be determined. This is somewhat greater than the depth generally found under oceans and considerably less than the depth under the continents. The Gulf of Maine may then be a transitional zone between oceanic and continental structures. The abundant data on the upper layers and the uniform subbasement make this an ideal place to study this transition.

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LAMONT GEOLOGICAL OBSERVATORY (COLUMBIA UNIVERSITY), PALISADES, N. Y.

MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, SEPTEMBER 18, 1953

LAMONT GEOLOGICAL OBSERVATORY CONTRIBUTION NO. 114

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 65, PP. 971-1006, 4 FIGS., 1 PL. OCTOBER 1954

# VIRGIN FORMATION (TRIASSIC) OF THE ST. GEORGE, UTAH, AREA

BY STANISLAW J. POBORSKI

## ABSTRACT

Marine sediments constituting the Virgin limestone member of the Moenkopi formation in the St. George, Utah, area represent an easily mappable lithologic unit that unconformably overlies the continental strata of the lower red member of the Moenkopi formation and the alpha member of the Kaibab formation. It is conformably overlain by the continental middle red member of the Moenkopi.

The Virgin limestone "member" is raised to formational rank, and, consequently, the Moenkopi "formation" is made a group.

The limestone content of the Virgin formation averages about 30 per cent of the sediments; consequently the lithologic term "limestone" has been dropped from the formational name.

The Virgin formation was deposited under a near-shore, shallow-water, marine environment. Cyclic sedimentation characterizes the lower part of the formation, the cycles consisting of basal limestones overlain by siltstones. The upper part of the formation in the southeastern area was deposited in restricted lagoons under an arid environment, while at the same time marine deposition persisted in the northern part.

Ammonites, identified by Prof. S. W. Muller as *Tirolites spinosus* Mojsisovics *s. l.*, *?Cordillerites*, and *?Hungarites*, were found near the middle of the formation. These definitely establish the stratigraphic position of the Virgin formation as near the top of the Lower Triassic sequence and indicate a Middle Triassic age for post-Virgin Moenkopi strata.

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## Introduction

### *The Area*

This study of a part of the Lower Triassic deposits in the St. George, Utah, area was undertaken at the suggestion of Dr. H. E. Vokes of The Johns Hopkins University, and of Dr. J. B. Reeside, Jr., of the U. S. National Museum, to increase our knowledge of geology of that area. On the advice of Professor E. D. McKee of the University of Arizona, who had just prepared a comprehensive report on the Moenkopi formation of the Colorado Plateau, the field work was limited to the Virgin limestone member of the Moenkopi formation west of St. George, Utah, in the area limited by U. S. highway 91 to the northwest, and by the Virgin River to the southeast (Figs. 1, 2). The field work occupied two summers, 1950 and 1951.

### *Acknowledgments*

The writer wishes to acknowledge his indebtedness to Professors H. E. Vokes and E. D. McKee for much valuable advice and constructive criticism. The writer profited considerably from frequent discussions with Professor E. D. McKee in the area studied and in the Geological Laboratory of the Museum of Northern Arizona.

Many thanks are extended to Professor Aaron C. Waters of The Johns Hopkins University for suggestions regarding the petrography; to Professor Siemon Wm. Muller of Stanford University for his identification of the cephalopods; and to Dr. Leif Størmer of the Paleontologisk Institut Styrer in Oslo, Norway, for the identification of the crustaceans.

Helpful assistance of Mr. A. D. Chesney in the field during the summer 1950 is greatly appreciated.

### *General Considerations*

Geologic studies of the St. George, Utah, area go back to Marcou (1858). Since then several geologists contributed to the knowledge of the Permian and Triassic problems of northwestern Arizona and southwestern Utah (Powell, 1875; 1876; Gilbert, 1875; 1880; Walcott, 1880; Dutton, 1882; Ward, 1900; 1901; 1905; Huntington and Goldthwait, 1904; Lee, 1907; Gregory, 1917; 1938; 1948; 1950; Gregory and Moore, 1931; Gregory and Anderson, 1939; Gregory and Williams, 1947; Butler *et al.*, 1920; Dake, 1920; Noble, 1922; Reeside and Bassler, 1922; Baker *et al.*, 1927; Gilluly and Reeside, 1928; Dobbin, 1939; McKnight, 1940; Gardner, 1941). The subdivision of the Moenkopi formation in the St. George, Utah, area into six members was introduced by Reeside and Bassler (1922).

Within the sequence that includes marine limestones of the Moenkopi, the third member from the base of the formation—the marine "Virgin limestone member" of Reeside and Bassler—forms an easily mappable lithologic unit. The writer suggests that it be given formational rank. The term "Moenkopi group," therefore, should be used for all lithologic units that have been known collectively as the "Moenkopi formation."

The stratigraphic units above and below the Virgin formation should be considered as distinct formations. How they should be grouped and defined and what they should be called must be left for future studies.

## Virgin Formation

### *Original Definition of the "Virgin Limestone Member"*

Reeside and Bassler (1922, p. 60) proposed "the name Virgin limestone member for the second unit above the basal conglomerate of

FIGURE 1.—DISTRIBUTION AND THICKNESS OF THE VIRGIN FORMATION IN SOUTHWESTERN UTAH
The numbers refer to sections in Table 1. Numbers in parentheses show the thickness of measured sections.

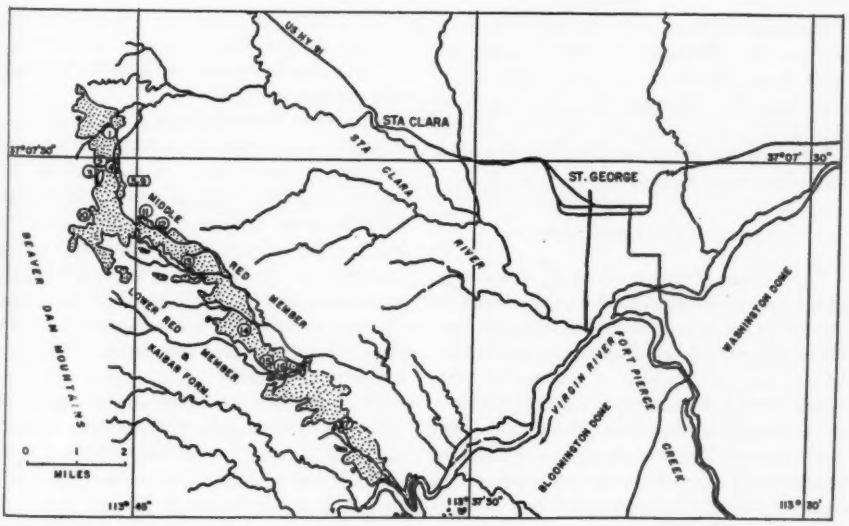


FIGURE 2.—AREAL EXTENT OF THE VIRGIN FORMATION COVERED BY THE PRESENT STUDY
Numbers in circles refer to the measured sections.

the Moenkopi formation, from Virgin City, where the unit is splendidly exposed." They (Reeside and Bassler, 1922, section 13) selected the section exposed in Smith's Mesa, 3 miles north of Virgin City, Utah, to represent the type section. They described the Virgin limestone "member" and listed the fossils in the limestones, as follows:

| | Feet |
|---|---|
| "Virgin limestone member; | |
| Limestone, yellow, earthy, fossiliferous; contains *Myalina* n. sp., *Pseudomonotis* n. sp., *Bakewellia* n. sp. | 5 |
| Shale, yellow and red | 25 |
| Limestone, yellow, earthy, fossiliferous; contains *Myalina* n. sp., *Pseudomonotis* n. sp. | 25 |
| Shale, yellow, calcareous | 25 |
| Limestone, fairly massive, yellow, earthy; contains *Isocrinus* sp., *Spirorbis* sp., *Terebratula*? n. sp., *Pinna*? sp., *Bakewellia* n. sp., *Pseudomonotis* n. sp., *Myalina* n. sp., *Aviculipecten*, 4 sp., *Myophoria*?, sp., *Pleurophorus*? sp., *Pleurotomaria*?, 2 sp., *Naticopsis* sp., ammonite ? undet. | 20 |
| Thickness of Virgin limestone member | 80 |

The paper of Reeside and Bassler is the only one on the Moenkopi in which fossils are listed from the strata in which they occur. Unfortunately, determinations are made to genera only, so the lists do not aid in correlation beyond the immediate area. Many species are undescribed and are poorly preserved.

### *Question of Nomenclature*

The "Virgin limestone member" in the type section north of Virgin City contains about 40 per cent limestone and at least 30 per cent calcareous mudstone (Reeside and Bassler, 1922, p. 73). The validity of the term is questioned west of the Hurricane fault, where limestone occupies not more than 20 per cent of the marine strata. The writer proposes to drop the lithologic term and henceforth to refer to the stratigraphic unit as the Virgin formation.

The Virgin formation thins from the northwest toward the southeast (Table 1). The facies changes from marine in the west to continental in the east. There is, however, more limestone east of the Hurricane fault than to the west. The limestone of the Virgin "member" in the type locality (Reeside and Bassler, 1922, p. 73) may correspond to the limestones of the lower part of the Virgin formation in the St. George area (Fig. 3), but the upper part of the Virgin formation in the St. George area may be represented by the lower portion of the "middle red member" on Smith's Mesa.

### *Boundaries of the Virgin Formation*

The lower boundary of the Virgin formation is placed at the base of the lowest limestone layer. In every locality in the St. George area examined by the writer, this limestone rests disconformably upon either the "lower red member" of the Moenkopi group or upon the alpha member of the Kaibab formation. The contact is an erosional surface. Possibly a low angular unconformity occurs at the base, but no evidence could be detected during field work.

The disconformity between Virgin strata and those of the "lower red member" was observed in 1879 by Walcott (1880, p. 222) in the Kanab Valley; by Gregory and Williams (1947, p. 231) in the Zion National Monument area; by Gregory (1950, p. 31) in eastern Iron County, Utah. It has been noted by the writer at every locality visited both within and outside the area.

The upper formation boundary in the area is placed at the top of the highest silty chert or limy siltstone layer, directly above the highest limestone. Calcite crystals fill or partially fill small cavities in the siltstone and/or chert. The cavities once contained marine invertebrate fossils, mainly small pelecypods, gastropods, and brachiopods, which have been replaced by calcite. Preservation of the fossils is very poor, and even generic identification is difficult or impossible.

The siltstone-chert layer at the top of the Virgin is conformably overlain by brown or dark-brown, gypsiferous, shaly siltstone of the "middle red member," believed to be continental. Thus, the boundary between the Virgin and the "middle red member" is marked by an abrupt change in lithology.

In the area the Moenkopi section includes both shore and near-shore deposits. During the retreat of the sea at the close of deposition of the Virgin formation, slight subsidences or

temporary lesser influxes of detrital materials may have caused ephemeral transgressions. Deposition farther west of one or more marine tongues younger than those in the St. George area would have resulted, in which case the boundary between the Virgin and the "middle red member" would be higher in the more westerly localities. Thus, the lithologic boundary at the top of the Virgin probably crosses time boundaries.

Table 1.—Thickness and Distribution of the Virgin Formation

| Number of section on base map | Thickness | Locality | Source of data and remarks |
|---|---|---|---|
| 1–17 | 162–213′ | 7–12 miles west and southwest of St. George, Utah | This paper |
| 18 | 100′ | Near Black Rock Spring, Arizona, about 25 miles south of St. George, Utah | Reeside and Bassler (1922, p. 75) |
| 19 | 160′ | Washington dome, 6 miles east of St. George, Utah | Reeside and Bassler (1922, p. 74) |
| 20 | 160′ | Harrisburg dome, 8 miles northeast of St. George, Utah | Reeside and Bassler (1922, p. 73) |
| 21 | 80′ | Smith's Mesa, 3 miles north of Virgin City, Utah | Reeside and Bassler (1922, p. 73) Type locality for the Virgin "member" |
| 22 | 115′ | La Verkin canyon, between Toquerville and Kolob, Utah | Huntington and Goldthwait (1904, p. 203) |
| 23 | 126′ | Deadman Hollow, 9 miles south of Kanarraville, Utah | Gregory and Williams (1947, p. 236). The authors included 29 feet of strata pertaining lithologically to "middle red member." |
| 24 | 119′ | Taylor Creek, 5.5 miles south of Kanarraville, Utah | Gregory and Williams (1947, p. 234–235); Gregory (1950, p. 96) |
| 25 | 100′ | 5 miles south of Kanarraville, Utah | Lee (1907, pt. II, p. 362) |
| 26 | 115′ | 2.5 miles south of Kanarraville, Utah | Gregory and Williams (1947, p. 231) |
| 27 | 130′ | Coal Creek, 0.5 mile east of Cedar City, Utah | Thomas and Taylor (1946, p. 21) report 190 feet for this locality. Gregory (1950, p. 82) found only 130 feet. |
| 28 | 11′ | 12.5 miles southwest of Fredonia, Arizona | Reeside and Bassler (1922, p. 70) |
| 29 | 44′ | 10 miles south of Fredonia, Arizona | E. D. McKee (Personal Communication 1951) |

### *Thickness of the Virgin Formation*

Table 1 demonstrates the thickening of the Virgin formation from the east and southeast toward the west and northwest (Fig. 1). Southwest of St. George the entire thickness is exposed only in a few sections. In many places the section is incomplete either because of recent erosion or because it is concealed.

### *Topographic Expression*

The Virgin formation may be recognized by its general gray color which contrasts with the enclosing red beds. Where the dip of the strata is slight, the formation weathers into considerably steeper slopes than does the "middle red member" above and the "lower red member" below.

The formation consists of a series of six to eight ledges with intervening slopes. Where strata dip slightly the inclination of the weak slopes that separate resistant ledges ranges from 22° to 38°. In most places the inclination is 32°–34°.

### *General Description of Sediments*

The formation is composed of limestone (20 per cent) and siltstone (80 per cent).

Limestones are massive, thick- to thin-

bedded, and laminated, forming layers up to 13 feet thick. Thickening and thinning within short distances, lensing, and changing lithology

Siltstones are interbedded with limestones. The siltstones are mostly dark gray or gray to brownish gray, but some strata are yellow gray,

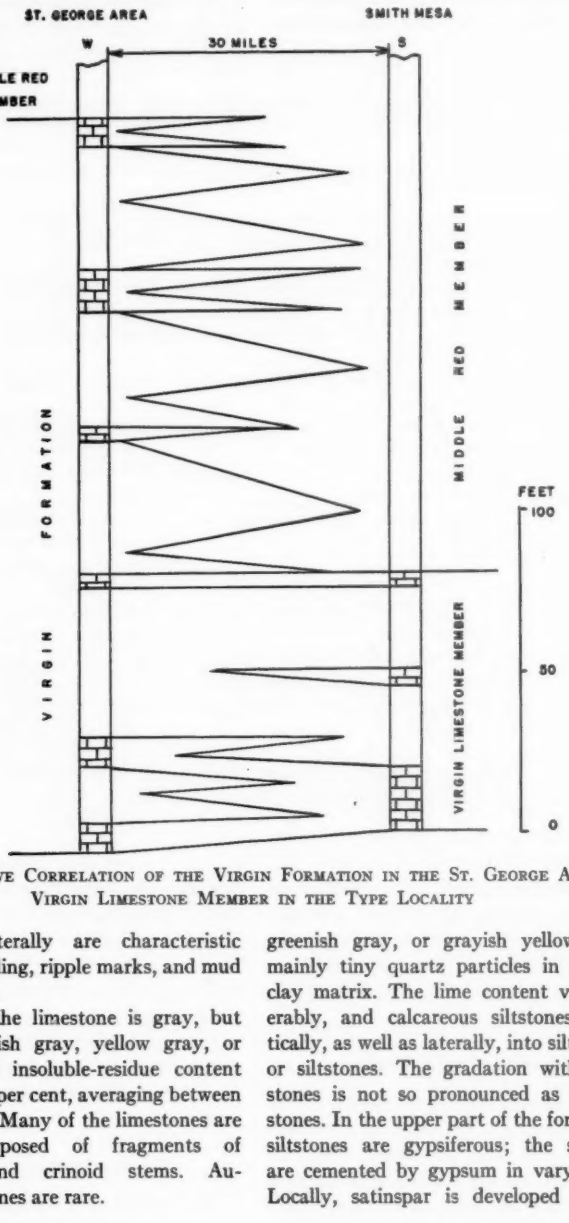


FIGURE 3.—TENTATIVE CORRELATION OF THE VIRGIN FORMATION IN THE ST. GEORGE AREA AND THE VIRGIN LIMESTONE MEMBER IN THE TYPE LOCALITY

vertically and laterally are characteristic features. Cross-bedding, ripple marks, and mud cracks are common.

In most places the limestone is gray, but locally it is greenish gray, yellow gray, or nearly white. The insoluble-residue content ranges from 0 to 50 per cent, averaging between 10 and 20 per cent. Many of the limestones are allochthonous—composed of fragments of mollusk shells and crinoid stems. Autochthonous limestones are rare.

greenish gray, or grayish yellow. They are mainly tiny quartz particles in a calcareous clay matrix. The lime content varies considerably, and calcareous siltstones grade vertically, as well as laterally, into silty limestones or siltstones. The gradation within the siltstones is not so pronounced as in the limestones. In the upper part of the formation some siltstones are gypsiferous; the silt particles are cemented by gypsum in varying amount. Locally, satinspar is developed in fractures

and along bedding planes. The gypsiferous siltstones are thickest toward the southeast.

On fresh surfaces bedding may not be visible in the siltstones, except where marked by grain size or by intercalation of thin, lenticular layers of limestone. Weathered beds show shaly or fissile bedding. Single beds range from a fraction of an inch to over 66 feet thick; the average is 16 to 26 feet. The siltstone layers, like the limestones, tend to be lenticular. Sandy laminae marking planes of structure occur locally in the siltstones, but beds of sandstone have not been observed.

Fossils, mainly pelecypods and some brachiopods, occur in the calcareous siltstones. Cephalopods are rare and are limited to one siltstone layer in the middle of the formation. Small arachnidlike arthropods, referable to *Halicyne*, have been found in one place, close to the top of the formation. Ostracods are locally common in the upper part of the formation.

In spite of the well-marked unconformity at the base of the Virgin, no basal conglomerate has been observed. In the lowermost parts of a few limestone layers are pebblelike inclusions of siltstone, apparently derived from underlying strata. These intraformational inclusions are up to 4 inches in diameter and are angular to subrounded. Where concentrated they form thin, irregular layers of fine conglomerate.

Other intraformational conglomeratic layers are in lenses of gypsum among the siltstone beds that underlie the uppermost limy siltstone. The main components of these conglomerates are angular fragments of gypsiferous siltstone.

## Stratigraphic Sequence

The sequence of the Virgin formation is presented in Figure 4 and Plate 1. References in the text to a single layer or any part of it are made by using the sample number (*e.g.*, P-361), which is also marked at the corresponding layer on the stratigraphic columns (Pl. 1). The designation of facies of single units are made by subscript numbers following the letter by which the unit is denominated (*e.g.*, Q, $Q_1$, $Q_2$).

## Unconformities and Disconformities in the Sections

### *Kaibab-Moenkopi Unconformity*

The Kaibab-Moenkopi unconformity has been discussed by many geologists, and the evidences of unconformity have been summarized by Longwell (1925) and McKee (1938, p. 54–61).

The Kaibab formation was not uniformly uplifted and eroded before deposition of the Lower Triassic strata began. Pronounced local upwarping resulted in the erosion of relatively deep valleys in some places, as observed in the Colorado Plateau and adjacent areas.

Local warping and erosion have been noted in some parts of the St. George area, where the two lowest "members" of the Moenkopi group and, in some places also, the two lowest units of the Virgin formation are missing. As a result, the Virgin formation locally is deposited directly upon the alpha member of the Kaibab formation (Fig. 4, sections 16, 17). This may have been due either to nondeposition on an eroded, or locally uplifted and eroded surface, or to erosion.

### *"Lower red member"-Virgin Formation Unconformity*

An unconformity between the Virgin formation and the "lower red member" is exhibited wherever the two are in contact. The absence of guide fossils above and below this unconformity prevents estimation of the duration of the hiatus. The time was sufficient, however, for consolidation of the lower sediments, as their fragments form inclusions immediately above the unconformity.

### *Disconformities Within the Virgin Formation*

With one exception, at the base of unit "U", disconformities occur between siltstones and overlying limestones in the Virgin formation. Other very local minor depositional breaks or diastems are developed in limestones and siltstones of most sections studied. One of many examples is an intraformational conglomeratic

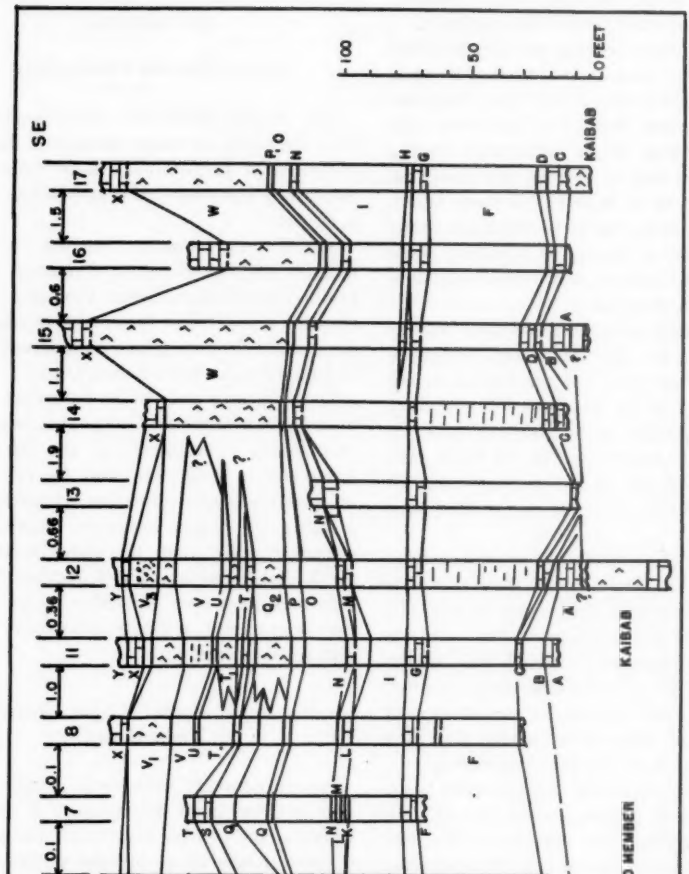


FIGURE 4.—SCHEMATIC CORRELATION OF THE SELECTED MEASURED SECTIONS OF THE VIRGIN FORMATION IN THE ST. GEORGE, UTAH, AREA

lens (P-275) in the upper part of siltstone of unit "F" in section 11 (Pl. 1).

A striking example of depositional break is in the group of limestones of units "C", "D", and "E" (Pl. 1). Cross-bedded limestone of unit "C" shows a bevelling of its upper part. An almost white crinoidal limestone "D" was deposited on previously bevelled limestone "C", in sections 1, 12, 13, 14, 16, and 17, while the boundary between these two limestones is marked by stylolites in section 15. Limestone "E", observed only in section 1, and "D" are about 7 feet thick. They are absent in other sections probably because of submarine erosion.

## Sedimentary Types and Environmental Conditions

### *General Statement*

The Virgin formation consists of rocks of varied lithology and origin. Siltstones of marine, brackish water, and lagoonal facies form the bulk of the formation. Limestones represent about 20 per cent of the rock; evaporites are present only locally.

Intertonguing of the marine and lagoonal facies occurs especially in the upper part of the formation. The lagoonal facies is represented by evaporites and by siltstones cemented by evaporites. Marine facies are dominant in the north but thin out or grade laterally into lagoonal deposits toward the south.

### *Siltstones*

*General.*—On the basis of lithologic character and the environment of deposition, the siltstones may be divided into (1) marine, gray siltstones; (2) marine, brown siltstones; (3) calcareous, gypsiferous, brown siltstones; (4) noncalcareous, gypsiferous, brown and light-gray siltstones; and (5) coprolitic siltstones.

*Marine gray siltstones.*—Marine, gray siltstones, though best represented in the lower part of the formation, form three-quarters to four-fifths of the entire unit. In the north they occur in both the upper and lower parts of the formation but, farther south, they grade laterally into reddish-brown siltstones. These siltstones rest with gradational contact upon limestones and are overlain by limestones.

The contact of siltstones with overlying limestones is sharp, and the lithology of the uppermost parts of the siltstones suggests a break in sedimentation, exposure to atmospheric action, or a change in the environment from marine to brackish or fresh water.

The siltstones are chiefly gray, grading into brownish gray or dark gray. The transition zones from limestone to siltstone are mostly greenish gray or bluish grading upward into the prevailing gray or brownish gray of the main body of siltstone. Insignificant thin, irregular layers or laminae of dark-gray or light-gray silt occur within the main body of siltstone.

The uppermost 4 inches to 1 foot 4 inches of the siltstones is lighter than the rest of the rock and is distinct greenish gray or yellow green gray. The change in color probably results from a change in conditions of deposition and is followed by an abrupt change from siltstone to limestone.

The siltstones are mainly angular and subangular or subrounded grains of quartz and minute plates of muscovite in a matrix of clay. The per cent of silt-sized particles diminishes upward in a unit, forming layers which range from siltstone immediately overlying limestone through clayey siltstone in the middle to silty claystone at the top of the unit. Only in siltstone of unit "T" (Pl. 1) does the amount of silt increase upward.

Locally, thin layers of nearly pure claystone are intercalated with almost pure siltstone. Some thin laminae of very fine-grained sandstone occur within the siltstone, and silty laminae separate nearly pure claystone layers. Although there are no major sandstone units, a few lenticular layers of very fine-grained sandstone, up to 4 inches thick, are present. Grain size in the siltstones varies vertically within single layers, even where the thickness does not exceed half an inch.

Nearly all grayish siltstones have calcareous cement, but none is entirely free of lime. The amount of calcareous cement progressively decreases from the base to the top of the siltstone unit. The uppermost 4–8 inches of the gray siltstone units locally has the lime entirely leached out.

The $CaCO_3$ content in some siltstones in-

creases upward within the unit, as in units "F" and "V". In these it forms layers of silty limestone, 1–2 inches thick, interbedded with moderately limy siltstone.

The lithology and faunas of the gray siltstones indicate a marine environment of deposition. Their composition and structure suggest that sediments were laid down in relatively shallow, quiet waters or on extensive tidal plains which were occasionally exposed to subaerial weathering. Intermittent subsidence of the sea floor probably initiated new periods of deposition which continued until the sedimentary basin was again filled, causing withdrawal of the seas.

During regression, the uppermost strata of the gray siltstone units apparently were exposed either to atmospheric conditions or to the action of fresh or slightly brackish water. Such changes in environment removed the $CaCO_3$ from the uppermost strata and leached them. A thin reddish stratum at the top of a leached zone in one place suggests either a change in the source of the clastic material, a different environment of deposition, or weathering.

Uniform size of detrital particles, and presence in the siltstones of only very stable minerals like quartz and muscovite, suggest transportation or reworking by the sea which eliminated less stable minerals. This implies either (1) a distant source area for the components of the sediments, and extremely slow transportation, such as would be possible only with a very broad coastal plain; or (2) their derivation from already well-sorted sediments; or (3) a long time of reworking before final deposition.

*Marine brown siltstones.*—The group of siltstones referred to as "marine brown siltstones" is represented by units "$I_1$" and "$Q_1$". Siltstone of unit "$Q_1$", which occurs in the upper part of the northern sections (1–8), overlies unit "Q", a typical marine gray siltstone, while unit "$I_1$", present only in the middle of section 11, overlies "I", also a normal marine gray siltstone.

Contacts of the marine brown siltstones with the underlying units of gray siltstone are clearly marked, but the relations are conformable. The two types of siltstone differ mainly in color. The marine, brown siltstones are overlain disconformably by limestones, except in section 1, where the unit "$Q_1$" apparently is overlain conformably by the very limy siltstone, "R".

These siltstones are brown, brownish gray, or dark brownish gray, with a few streaks of greenish gray formed by silt. The siltstones are mainly silt-sized particles of quartz, minute flakes of muscovite, and a matrix of clay. Very small grains of magnetite form a thin film on uneven bedding planes. Laminae of silt in unit "$Q_1$" of section 6 are distinct greenish gray. Their lime content is abnormally high for these brown siltstones.

The siltstone of unit "$Q_1$" in the uppermost 1 foot 4 inches is light gray. Thin layers are interbedded with greenish-gray claystone and contain, in the middle, limy yellow laminae of claystone. This unit is calcareous and grades laterally, south of section 8, into gypsiferous siltstones of lagoonal origin (Fig. 4).

No fossils have been found in these siltstones. The ripple marks and mud cracks in the brown siltstones suggest formation in very shallow marine waters in a basin always filled or nearly filled with sediments.

*Calcareous, gypsiferous siltstones.*—A group of siltstones transitional between marine and continental strata is represented by units "$Q_2$", "$T_1$", "$V_1$", and "$V_2$". This group occurs in the upper part of the stratigraphic columns, north of section 14.

The calcareous, gypsiferous siltstones grade laterally into marine gray siltstones toward the northwest, and into lagoonal sediments toward the southeast. The highest siltstone, "$V_1$", reaches farthest north. Each unit is set off by sharp lithologic boundaries both above and below. The upper boundary is everywhere disconformable.

The calcareous, gypsiferous siltstones range from dark brown, through brown, to brownish gray. Some of the most strongly gypsiferous beds, however, are distinctly gray or greenish gray, as siltstone P-286 and unit "$T_1$" in section 11. Thin layers of greenish-gray siltstone (up to 1 cm thick) alternate in most places with brown siltstone, especially in the upper parts of the units.

The siltstones are mainly quartz grains of

silt size or smaller, mostly well sorted and graded. A few laminae of sandy siltstone occur in the upper part of unit "$V_1$" in section 6. Very small magnetite crystals are disseminated throughout and locally are concentrated to form a thin film on bedding planes.

The cement consists largely of gypsum and minor calcium carbonate. Gypsum also occurs in irregular layers that are progressively more abundant and thicker toward the top of each calcareous, gypsiferous siltstone unit. Individual layers of gypsum range up to 4 inches thick. The upper part in most of the units is composed of laminae of gypsum. Veins of satinspar are found in fractures.

Layers of gypsum are associated in many places with gray siltstones of the calcareous, gypsiferous siltstone group. Where the relative abundance of gypsum cement is great, the particles of silt are suspended in crystals of gypsum, forming green-gray layers of "gypstone" (Shrock, 1948, p. 65, used the name "gyprock") that are more resistant to weathering than the surrounding rocks.

Above "$V_1$" in section 6 is a layer of gray, silty and limy, shaly claystone and siltstone 1 foot 8 inches thick, unit "$V_2$". In the middle of this unit occur three yellow-brown or brownish-gray layers, each about 1 inch thick. On top of the unit are ripple marks 4 inches in amplitude and 2 feet long.

No traces of life have been noted in the calcareous, gypsiferous siltstones. The presence of calcareous and gypseous cement, and the intercalation of gypsiferous layers with dominantly calcareous layers, especially in the upper parts of the units, indicate deposition under conditions unfavorable to life. There seems to have been wide fluctuation in the relative amount and concentration of carbonate and sulfate ions, or in the conditions that resulted in the precipitation of one or the other.

*Noncalcareous, gypsiferous siltstone.*—The noncalcareous, gypsiferous siltstone of unit "W" was not examined because of poor exposure. This rock is brownish gray and reddish brown. It has a fine, uniform grain size and contains thin-bedded and laminated layers of gypsum.

Two types of gypsum occur in the noncalcareous, gypsiferous siltstone unit. One is greenish gray, has a ribbonlike lamination, and contains silty particles in varying concentrations; the other consists of white, crystalline gypsum, thin-bedded and lenticular in most places.

A very slight calcium-carbonate content has been noted. From the scant data available, it is believed to have formed under lagoonal conditions.

*Coprolitic siltstone.*—Conformably overlying unit "$Q_1$" in section 1 is unit "R", designated as "coprolitic siltstone" 12 feet thick. It is not known from any other section. It is disconformable with overlying limestone.

The coprolitic siltstone is light yellowish-brown in its lower part and grades upward into light yellowish-gray.

The lowest 2–3 feet of the rock is mainly silt-sized, angular and subangular quartz and fine-grained muscovite. The component grains are finer toward the top of the unit. In the uppermost part of unit "R" the detrital particles are clay size, but subrounded grains of white quartz, ranging up to 1 mm in diameter, are scattered throughout the fine matrix.

The very fine material in the uppermost 2 feet of unit "R" is aggregated into loosely cemented pellets, irregular in size and shape, but mostly spherical or ovoid. They are composed of a brownish clay and dissolve in hydrochloric acid, coloring it brown to dark-brown.

The lowest part of unit "R" is uniformly soft, thin-bedded, and laminated. The middle part consists of alternating soft and hard, thin-bedded and laminated layers. Laminae, 1–5 mm thick in the soft layers, are arranged in groups up to 2 inches thick. These alternate with harder layers of about the same thickness. The harder layers contain well-developed ripple marks. In the uppermost 2 feet of the unit, bedding is hardly visible.

Layers of iron-coated grains mark the bedding of the coprolitic siltstone, especially in the lower part. Some dark-brown spots occur throughout. Under the microscope, these spots appear to be formed from groups of minute quartz grains coated with hematite.

The coprolitic siltstone is porous and not well cemented. Porosity is progressively greater to-

ward the top. Field and laboratory tests show a low calcium-carbonate content.

The only fossils known are impressions of indeterminate small pelecypods in the lowest 3 feet and some very poorly preserved, small gastropods in the uppermost 2 feet.

The origin of the pellets that form the uppermost 2 feet of the coprolitic siltstone unit is debatable. They may be a faecal product of bottom-dwelling macro-organisms. Most have a simple ovate shape, but some resemble faecal pellets of Littorinidae illustrated by Moore (1931, Pl. 33).

Recent studies of sediments of the sea bottom (Dapples, 1942) show a wide distribution of coprolitic material at various depths. Tidal flats are one of the best environments for bottom dwellers that may greatly influence the accumulating sediments. Studies of recent tidal-flat deposits along the North Sea in Germany (Hantzschel, 1939) have shown that ellipsoidal excrements of polychaete worms and certain pelecypods living in the upper few cm of the deposits, and of gastropods *Littorina* and *Hydrobia* that feed on the surface of the deposit, may form a major part of the sediment.

Such material reworked on the sea floor by bottom-dwelling organisms may reach great thickness; in the Virgin formation it amounts to over 2 feet. Dapples has suggested that such organic "reworking" of sediments probably would destroy all traces of bedding.

The characteristics of the uppermost 2 feet of unit "R", and the similarity of the pellets to those of known faecal origin suggest that these uppermost strata should be interpreted as coprolitic. Coprolites have been observed locally also in the siltstones of unit "V".

*Color of siltstones.*—The color of the sediment components may solve the problem of the origin of the source material and of the environmental conditions during sedimentation, lithification, and diagenesis.

RED BEDS: The origin of red beds has been given much attention by many writers, including Branson (1915), Dorsey (1926), and Krynine (1949).

The siltstones of the Virgin formation are mainly gray or "red." A true red is extremely rare in the formation and, when present, is of a limited, strictly local character. The term "red" as applied in the literature to "red beds" of the Moenkopi "formation" has been used for predominantly brown siltstones.

The mineral components of the sediments suggest the same source of the clastic material for both gray and brown siltstones. The silt particles imply a distant source area and slow transportation over a very broad coastal plain, or a long time of reworking. Nothing can be deduced from the sediments as to the source area itself.

Coastal plains over which the sediments may have been transported have not been recognized. An exception may be the alpha member of the Kaibab which could have contributed to the gypsiferous deposits of the Virgin formation.

Deposition took place in lagoonal, brackish-water, and marine environments, with lateral change of facies from continental (lagoonal) to marine. The brown siltstones may have been formed: (1) from detritus of existing red beds, reworked and sorted during transportation and deposited under the climatic conditions which permitted the preservation of red pigment; or (2) from nonred detrital rocks, the components of which acquired red pigment from the oxidation processes affecting ferruginous minerals during long transportation under relatively humid and warm climatic conditions and were deposited in an environment that preserved the red color; or (3) from nonred detrital rocks, the red color resulting from the oxidation of ferrous into ferric oxide in the depositional basin in the absence of reducing agents.

Under a normal marine, open-circulation environment the oxidation-reduction potential, Eh, has small positive value (0.2–0.4), and sea water represents mildly oxidizing conditions throughout. Chemical end members, stable in the oxidizing environment, are not subject to severe chemical change when buried in such an environment (Krumbein and Garrels, 1952, p. 27).

The precipitation of the red iron-oxide pigment from solution is improbable in the case of the "red" siltstones of the Virgin formation. The pigment occurs as a coating on silt grains, and not as a matrix or as concretions, as would be expected in the marine oxidates precipitated largely as gels.

The "red" color of the gypsiferous siltstones of the Virgin formation (unit "W", and its tongues "$Q_2$", "$T_1$", and "$V_1$") may be explained as follows:

The ferric oxide-coated grains of silt were blown by wind or transported by water during occasional cloud bursts into near-shore lagoons. The high salinity of these lagoons inhibited organic life, resulting in conditions which prevented or limited the reduction of the ferric oxide pigment.

Under a restricted arid environment high temperatures reduced the oxygen content and may have decreased the Eh value. The primary gypsum content in the matrix of some of the brown siltstones indicates that the prevailing water temperature during deposition was about 30°C.

The presence of gypsum both as cement in the "red" siltstones and as layers of almost pure material interbedded with siltstones, and absence of any traces of carbonaceous matter which could have caused reduction of iron-bearing minerals suggest subsequent deposition of primary red sediments in the zone of oxidation of shallow, lagoonal waters.

GRAY SILTSTONES: The gray siltstones range from bluish, through dark gray, to greenish gray or even green. Considering these colors there are following possibilities:

(1) Primary reddish sediments may have been reduced in the basin of deposition. The reduction may occur in the presence of organic matter decaying under anaerobic conditions and change the hydrous ferric oxide into sulfides or carbonates (Ruedemann, 1925, p. 85). Depending on the degree of reduction the color ranges from blue to green. According to Pettijohn (1949, p. 173) abundant carbon in the strata will inhibit oxidation of the iron and will reduce the higher oxides to the lower. In the absence of organic matter the sediment cannot change its red color by the reduction of ferric oxide into ferrous oxide.

Reducing conditions may also occur where the currents carrying oxygen-bearing surface water do not reach the bottom, or where the surface waters have been deprived of their oxygen by biological activity (Rankama and Sahama, 1950, p. 214).

(2) Primary nonred sediments may be deposited in the presence of organic matter which inhibits or limits the oxidation. A low degree of oxidation will give colors ranging from blue to green (ferrous oxide). In the absence of carbon or other reducing agents the sediments may retain their primary colors which may range from white to black.

### *Limestones*

*General.*—The limestones in the Virgin formation may be divided into: (1) silty limestones, (2) crinoidal limestone, (3) oölitic limestone, (4) chemically precipitated limestone, and (5) siliceous limestone. There are no wholly clastic, or any pure, chemically precipitated limestone in the formation. Considerable clastic material may be found in the lower part of the layer, and almost pure, probably chemically precipitated limestone near the top of the same layer. There is also a considerable lateral lithologic change, and the same layer may show marked lateral facies variation.

*Silty limestone.*—Most of the limestones may be classified as silty limestone, usually gray, ranging from slightly dark, through green, to olive-green, bluish, and light-green hues. Locally yellow or brownish-yellow colors are present, especially in the layers in the oxidizing zone. They contain essentially no carbonaceous matter. The organic material of decaying animals may have limited or prevented the oxidation of ferrous oxides or may have reduced the ferric oxides to ferrous oxides.

The insoluble residue in the limestones ranges from 1.1 to 50.0 per cent with the average content ranging from 15 to 25 per cent. Usually, it is higher in the lower parts of the limestones and diminishes toward the upper part of a single unit, where it tends to increase again forming a transition into the overlying siltstone. There are, however, units in which the insoluble residue content progressively increases toward the top.

The most common insoluble components of the silty limestones are, in order of decreasing abundance: angular and subangular to subrounded grains of quartz; locally, irregular, small aggregates of opal; and iron oxides, present usually as irregularly shaped, powdery aggregates and as a very fine coating on quartz grains. Hornblende (and possibly hypersthene),

galena, flakes of muscovite, and some feldspar are rare. They are disseminated throughout the rock although locally they may be concentrated in thin layers. A few irregular laminae of clay minerals cemented by opal are embedded in limestone.

The silt in the lowermost parts of limestone units may be concentrated into thin laminae of limy siltstone. The limestones that contain less than 10 per cent silty material have a fine crystalline texture. Those that are finely crystalline are dense and break with a conchoidal fracture.

The boundary between limestones and the underlying siltstones is always distinct. The upper boundary, between the limestones and the overlying siltstones, is not so prominent and is transitional. The silt content increases up to 50 per cent in the uppermost transitional part of the units.

The limestone of unit "G" locally is coprolitic. Marine fossils were observed in the silty limestone units throughout the formation. Most of the fossils are very poorly preserved, and many are replaced by calcite.

*Crinoidal limestone.*—This limestone is represented by unit "D" in sections 1, 10, and 12 to 17 (Fig. 4). The limestone ranges from almost white in the most northern locality, section 1, to light-gray in the southeastern sections. The color depends on the amount of insoluble residue. The nearly white limestone of section 1 contains less than 1 per cent, while the residue content in the darker (light-gray) limestones ranges from 3 to about 32 per cent.

The main components of these limestones are broken stems and plates of crinoids, entirely recrystallized. They are well sorted and of a uniform coarse size. A few fragments of thin-shelled terebratulids and aviculopectinid pelecypods are locally present. Like the insoluble residues they increase from the northwest toward the southeast, while the relative abundance of crinoid fragments diminishes in the same direction.

The cement of the crinoidal limestone is calcareous. A few small, irregular cavities have the walls covered by a thin film of iron oxides.

The limestones are massive and do not show bedding, except for a weak indication of cross-stratification in section 15.

The crinoidal limestones of unit "D" were deposited in relatively shallow and clear water, as evidenced by a low amount of silt in the most northern section (1), where the crinoidal content is highest. Apparently the turbidity of the water increased farther south where the limestones of unit "D" contain more silty material suggesting shallower and more turbulent conditions and the proximity of a shore line.

*Oölitic limestone.*—Irregular, thin, oölitic layers of limestone were observed in the upper part of unit "X", in section 16. The limestone is yellowish gray, massive, and very finely crystalline. Large crystals of calcite are disseminated throughout.

The oöids range from oölitic to pisolitic dimensions and show a varied degree of sphericity. Nuclei of the oöids consist of one or more minute crystals of calcite or dolomite. No nuclei of other composition were found in thin sections or on polished surfaces. Concentric growth laminae of most oöids consist of alternating deposits of calcite and dolomite. Many, however, are entirely calcite or dolomite.

Locally, several oöids form small concretions, most of which are spherical, but which may be irregular in shape. The space between the oöids within the concretions is filled with large crystals of calcite. The oöid concretions serve as centers of crystallization and show further concentric aggregation.

The space between adjacent concretions and between concretions and the separate oöids is also filled by large crystals of calcite. The walls of a few cavities are covered by crystals of calcite or dolomite. We do not know what concentrated single oöids into concretions. Neither the oöids nor the concretions show any sign of abrasion or sorting, and oöids of different sizes occur together.

Oölites supposedly form from the precipitation of calcite about nuclei in strongly agitated, shallow waters (Eardley, 1938, p. 1386). They may form also in shallow waters by rolling and spinning movement of the particles (Kuenen, 1950b, p. 220). Eardley (1938, p. 1359), studying the modern sediments of Great Salt Lake, Utah, observed that the most favorable sites for oölite development are shore lines which, facing the open lake, receive the

action of unimpeded waves. He also states that "the more vigorous the wave activity the larger and more typically developed the oölites and ordinarily cleaner the oölitic sand" (p. 1371). Twenhofel (1939, p. 630) says that oölites and pisolites are known also from strata that show little or no evidence of wave or current action.

In the Virgin formation the amount of agitation of water during the formation of oölitic layers is unknown.

*Chemically precipitated limestone.* — Pure, chemically precipitated limestones are present only locally. The limestone layers may contain considerable clastic material in the lower part and may show characteristics of a chemical precipitate in the upper part of the layer.

Several layers, especially within units "A", "C", "S", and "X", which probably have been chemically precipitated, locally have finely to coarsely crystalline grains. Most finely crystalline limestones are flaggy or massive and structureless. The layers are lenticular, and some of them grade laterally into silty limestones.

A few of the chemically precipitated limestones are dolomitic and sideritic, as the basal part of the limestone of unit "S", in section 6. This yellowish-gray limestone occurs in lenticular layers, 1 to 2 inches thick, that alternate with gray, dense, massive limestone. Thin bedding and even lamination is visible, however, on weathered edges. The rock is dense and breaks with a conchoidal fracture. Only a negligible amount of insoluble residue is present. Dolomitic limestone is represented by 8- to 12-inch layers in unit "S", in section 2 and 3.

*Siliceous limestone.*—The uppermost limestone, unit "X", is finely crystalline composed of minute calcite crystals of uniform size. Locally, it is distinctly siliceous.

The insoluble residue, mainly silica, ranges from 1.6 per cent in relatively pure, crystalline limestone to about 30 per cent in distinctly siliceous limestone. The lateral variation of silica is more pronounced than the vertical variation in unit "X".

Silica is present in the siliceous limestones mostly as small euhedra of authigenic quartz and as small spherulites of authigenic chalcedony which is disseminated and also concentrated in small irregular aggregates. Other main components are detrital quartz, feldspars partly altered to clay minerals, and muscovite. There also are thin layers of clay cemented by opal.

The siliceous limestone is massive and structureless, but shows lamination and thin bedding on weathered surface. It is light gray to yellowish gray. The less siliceous layers, composed of coarser crystals of calcite, are light gray or gray.

Small gastropods, probably Pleurotomariidae, are present locally but are very poorly preserved.

### *Cherts*

Chert was observed in limestone mainly in unit "S" in section 2; in unit "Y", in sections 11 and 12; and only locally in unit "X". It occurs in unit "S" as irregular, thin layers or lenses and as disc-shaped concretions from half an inch to more than 2 feet in diameter, and up to 1 inch in thickness. The cherts are concordant with the bedding or cross-stratification and are also distributed at random within the massive beds.

Most of the centers of chert concretions are dense, but many show a spongelike structure and are quartzitic. A thin peripheral zone of the concretions is porous in all specimens, with the intergranular spaces filled by calcite, dolomite, or hematite. The walls of some cavities (intergranular spaces) are covered by minute crystals of hematite. The boundary between the concretions and the surrounding rock is well marked by the darker color of the peripheral zone.

A thin section of a cherty concretion from the limestone of unit "S", section 2, revealed a matrix of chalcedony surrounding (1) abundant carbonate in rounded and ellipsoidal grains, pellets, and crystals, some stained black, probably by organic matter; (2) scattered detrital grains of quartz, feldspar, and a few of muscovite; (3) large opaque spots, satiny white in reflected light, that appear to be leucoxene. There is no indication as to what the original titanium mineral was that has altered to leucoxene, or whether the leucoxene

was deposited as such; (4) large patches of opal, with cracks filled with secondary chalcedony that has crystallized from the opal; and (5) iron-stained patches of carbonate, possibly from the weathering of finely disseminated pyrite?. These probably are coprolites.

Other concretions may have formed from colloidal silica of sea water, which was attracted by clastic quartz grains or other centers of crystallization or concretion. The intergranular spaces may have been filled at the same time with carbonates and with iron oxides. These cherty concretions may be compared to quartzitic chert concretions described by McKee (1938, p. 88) as type 3, from the beta member of the Kaibab.

No fossils were observed in or near concretions. Some of the fossils in the limestone of unit "S" are replaced by chert, but they are not connected with existing cherty concretions.

### *Gypsum*

Gypsum, an important component of the siltstones of the upper part of the Virgin formation, is present in units "$Q_2$", "$T_1$", "$V_1$", "$V_2$", and "W". These units form layers 6 to 50 feet thick, with the thickness increasing from northwest to southeast.

The gypsum occurs as: (1) aphanitic gypsum in the matrix of siltstones, occurring with a small amount of calcium carbonate; (2) free crystals of gypsum embedded in the matrix; (3) satinspar in veins and in spaces between the laminae of the siltstone; and (4) ribbonlike layers.

The amount of silt suspended in the gypsum averages 20 per cent. The dark gypsum contains up to 50 per cent silt, but the light-gray or white gypsum may have not more than 12 per cent. The evaporite portion of the rock is predominantly gypsum, but a small amount of calcium carbonate is present in all specimens. The calcium carbonate in the matrix of the brown siltstones decreases from north to south.

There are two possible sources for the gypsum:

(1) It may have originated through precipitation from sea water that had concentrated it by evaporation in lagoons. Water could have broken through a barrier into the lagoons during storms, or there might have been a shallow connection between the lagoons and the sea. The lagoons could have been replenished periodically or constantly with sea water.

(2) It may have been carried in solution or blown by the wind, from areas where the alpha member of the Kaibab was being eroded, into depositional basins which were also occasionally receiving sea water.

The absence of deformation in the gypsiferous strata indicates that gypsum was directly precipitated and is not a product of hydration of anhydrite. Only a few ribbonlike gypsum layers in unit "W" show slight deformation. Syngenetic internal structures, such as ripple marks and ripple laminae in the gypsiferous siltstones, suggest a lagoonal, saline, shallow-water environment.

The absence of primary structures in parts of the strongly gypsiferous siltstones suggests uninterrupted deposition locally below the wave action. The greater density of lagoonal water caused by evaporation may have modified the waves, so their action was shallower than in the basins containing normal sea water. Small lagoons would also limit the amplitude of waves and diminish their influence on the sediments.

The conditions postulated for formation of the gypsiferous siltstones under restricted arid environment are found in modern lagoons. The classic example is the Gulf of Karabugaz, on the eastern side of the Caspian Sea, surrounded by desert on three sides. The average depth of the gulf is not more than 50 feet. It is separated from the Caspian Sea by narrow sand spits (Grabau, 1920, p. 132). A shallow, narrow (100–500 meters) strait, 5 km long, is the only connection with the Caspian Sea. The current passing through this strait always flows from the Caspian Sea toward the gulf. The current has a minimum velocity 24.5 meters per minute in November and increases to over 44 meters per minute during the summer, when the water level in the gulf falls because of increased evaporation. This stream carries into the gulf a daily load estimated at 350,000 tons of salt.

This gulf represents the extreme case for the formation of gypsum in considerable quantity.

The barrier does not permit the outflow of dense water from the gulf, while hydrostatic equilibrium causes the inflow of the "normal" Caspian Sea water into the gulf. The density of the surface water in quiet basins increases with evaporation, and the heavier water settles. Gypsum will precipitate from solution when the salinity increases to 3.5 times the normal concentration of sea water, at or near 30°C. The precipitation will continue until the salinity reaches approximately 4.8 times the normal salinity of sea water. Beyond this point the calcium sulfate will be precipitated as anhydrite. Hydrogen-ion concentration (pH) required for precipitation under restricted arid environment is 8 to 9. The pH value of the Caspian Sea ranges between 7.6 and 8.6 (von Raupach, 1952, p. 92). The pH increases with increasing salinity.

When gypsum was precipitated in the upper part of the Virgin formation, fine particles of clay or silt were being transported by wind or water into the depositional basin and may have formed nuclei for the precipitation of gypsum. The primary coating on silt grains is responsible for the "red" gypsiferous siltstones. The cement is hydrous calcium sulfate and calcium carbonate.

The association of gypsum with calcium carbonate has been noted by McKee (1938, p. 123) in Toroweap alpha, facies 1, from Hilltop, near Havasu Canyon, Arizona. There the gypsum is not replacing the limestone but fills fractures and cavities in older limestone.

In the gypsiferous siltstones of the Virgin formation, gypsum is the dominant mineral of the matrix. The gypsum did not replace the limestone, and it seems certain that gypsum and calcite were precipitated contemporaneously.

The association of calcium carbonate and gypsum has been briefly considered by Stieglitz (1909), Pia (1932), and others. Their conclusions are summarized below.

Considering a solution in which gypsum and calcite are in equilibrium the following formulae are obtained:

$$CaSO_4 \rightleftharpoons Ca^{++} + SO_4^{=}$$
$$CaCO_3 \rightleftharpoons Ca^{++} + CO_3^{=}$$

The constants of the ionic product (or dissociation) of a solution saturated with gypsum and calcium which are in equilibrium may be expressed:

$$[Ca^{++}]\cdot[SO_4^{=}] = ks \text{ (constant for S)}$$
$$[Ca^{++}]\cdot[CO_3^{=}] = kc \text{ (constant for C)}.$$

The valence of $Ca^{++}$ in both equations is the same, but the required amount of $Ca^{++}$ ions is much greater in calcium sulfate than in calcium carbonate (Pia, 1932, p. 20). From the equation

$$[SO_4^{=}]:[CO_3^{=}] = ks/kc$$

it may be calculated that the amount of sulfate ions in solution must be "about 5000 times greater" (Pia, 1932, p. 20); 4700 times greater (Stieglitz, 1909, p. 250) than that of carbonate ions, in order to maintain the equilibrium.

Under natural conditions the excess of sulfate ions is not so great as required to maintain the equilibrium. Thus, the carbonate precipitates first until the concentration of carbonate ions reaches a ratio 1/5000 that of the sulfate ions (the ratio ks/kc).

When in the solution, which is in equilibrium with both salts, the concentration of the sulfate ions is increased by an addition of a second sulfate (sodium or potassium sulfate), the solution is oversaturated with calcium sulfate and gypsum precipitates. The loss of calcium ions makes the solution undersaturated in regard to the carbonate, and some of the calcium carbonate present must pass into solution until the ratio 1/5000 is reached (Stieglitz, 1909, p. 251). Generally, calcium carbonate precipitates first as pure calcite until the conditions of equilibrium are re-established, and then, with advanced evaporation, a mixture of both calcite and gypsum precipitates.

A precipitation of a mixture of two minerals from solution is theoretically and practically possible (Findlay, 1900, p. 416–417). Under certain circumstances only an easier soluble salt may be precipitated. The separation depends on the constants of equilibrium.

Von Raupach (1952, p. 113) states that in Karabugaz-göl a layer 1 mm thick of sulfate-carbonate sediment is deposited yearly and that the solubility constants of carbonates and sulfates are influenced by the water temperature; sulfates precipitate in winter, and car-

ward the top. Field and laboratory tests show a low calcium-carbonate content.

The only fossils known are impressions of indeterminate small pelecypods in the lowest 3 feet and some very poorly preserved, small gastropods in the uppermost 2 feet.

The origin of the pellets that form the uppermost 2 feet of the coprolitic siltstone unit is debatable. They may be a faecal product of bottom-dwelling macro-organisms. Most have a simple ovate shape, but some resemble faecal pellets of Littorinidae illustrated by Moore (1931, Pl. 33).

Recent studies of sediments of the sea bottom (Dapples, 1942) show a wide distribution of coprolitic material at various depths. Tidal flats are one of the best environments for bottom dwellers that may greatly influence the accumulating sediments. Studies of recent tidal-flat deposits along the North Sea in Germany (Hantzschel, 1939) have shown that ellipsoidal excrements of polychaete worms and certain pelecypods living in the upper few cm of the deposits, and of gastropods *Littorina* and *Hydrobia* that feed on the surface of the deposit, may form a major part of the sediment.

Such material reworked on the sea floor by bottom-dwelling organisms may reach great thickness; in the Virgin formation it amounts to over 2 feet. Dapples has suggested that such organic "reworking" of sediments probably would destroy all traces of bedding.

The characteristics of the uppermost 2 feet of unit "R", and the similarity of the pellets to those of known faecal origin suggest that these uppermost strata should be interpreted as coprolitic. Coprolites have been observed locally also in the siltstones of unit "V".

*Color of siltstones.*—The color of the sediment components may solve the problem of the origin of the source material and of the environmental conditions during sedimentation, lithification, and diagenesis.

RED BEDS: The origin of red beds has been given much attention by many writers, including Branson (1915), Dorsey (1926), and Krynine (1949).

The siltstones of the Virgin formation are mainly gray or "red." A true red is extremely rare in the formation and, when present, is of a limited, strictly local character. The term "red" as applied in the literature to "red beds" of the Moenkopi "formation" has been used for predominantly brown siltstones.

The mineral components of the sediments suggest the same source of the clastic material for both gray and brown siltstones. The silt particles imply a distant source area and slow transportation over a very broad coastal plain, or a long time of reworking. Nothing can be deduced from the sediments as to the source area itself.

Coastal plains over which the sediments may have been transported have not been recognized. An exception may be the alpha member of the Kaibab which could have contributed to the gypsiferous deposits of the Virgin formation.

Deposition took place in lagoonal, brackish-water, and marine environments, with lateral change of facies from continental (lagoonal) to marine. The brown siltstones may have been formed: (1) from detritus of existing red beds, reworked and sorted during transportation and deposited under the climatic conditions which permitted the preservation of red pigment; or (2) from nonred detrital rocks, the components of which acquired red pigment from the oxidation processes affecting ferruginous minerals during long transportation under relatively humid and warm climatic conditions and were deposited in an environment that preserved the red color; or (3) from nonred detrital rocks, the red color resulting from the oxidation of ferrous into ferric oxide in the depositional basin in the absence of reducing agents.

Under a normal marine, open-circulation environment the oxidation-reduction potential, Eh, has small positive value (0.2–0.4), and sea water represents mildly oxidizing conditions throughout. Chemical end members, stable in the oxidizing environment, are not subject to severe chemical change when buried in such an environment (Krumbein and Garrels, 1952, p. 27).

The precipitation of the red iron-oxide pigment from solution is improbable in the case of the "red" siltstones of the Virgin formation. The pigment occurs as a coating on silt grains, and not as a matrix or as concretions, as would be expected in the marine oxidates precipitated largely as gels.

The "red" color of the gypsiferous siltstones of the Virgin formation (unit "W", and its tongues "$Q_2$", "$T_1$", and "$V_1$") may be explained as follows:

The ferric oxide-coated grains of silt were blown by wind or transported by water during occasional cloud bursts into near-shore lagoons. The high salinity of these lagoons inhibited organic life, resulting in conditions which prevented or limited the reduction of the ferric oxide pigment.

Under a restricted arid environment high temperatures reduced the oxygen content and may have decreased the Eh value. The primary gypsum content in the matrix of some of the brown siltstones indicates that the prevailing water temperature during deposition was about 30°C.

The presence of gypsum both as cement in the "red" siltstones and as layers of almost pure material interbedded with siltstones, and absence of any traces of carbonaceous matter which could have caused reduction of iron-bearing minerals suggest subsequent deposition of primary red sediments in the zone of oxidation of shallow, lagoonal waters.

GRAY SILTSTONES: The gray siltstones range from bluish, through dark gray, to greenish gray or even green. Considering these colors there are following possibilities:

(1) Primary reddish sediments may have been reduced in the basin of deposition. The reduction may occur in the presence of organic matter decaying under anaerobic conditions and change the hydrous ferric oxide into sulfides or carbonates (Ruedemann, 1925, p. 85). Depending on the degree of reduction the color ranges from blue to green. According to Pettijohn (1949, p. 173) abundant carbon in the strata will inhibit oxidation of the iron and will reduce the higher oxides to the lower. In the absence of organic matter the sediment cannot change its red color by the reduction of ferric oxide into ferrous oxide.

Reducing conditions may also occur where the currents carrying oxygen-bearing surface water do not reach the bottom, or where the surface waters have been deprived of their oxygen by biological activity (Rankama and Sahama, 1950, p. 214).

(2) Primary nonred sediments may be deposited in the presence of organic matter which inhibits or limits the oxidation. A low degree of oxidation will give colors ranging from blue to green (ferrous oxide). In the absence of carbon or other reducing agents the sediments may retain their primary colors which may range from white to black.

### *Limestones*

*General.*—The limestones in the Virgin formation may be divided into: (1) silty limestones, (2) crinoidal limestone, (3) oölitic limestone, (4) chemically precipitated limestone, and (5) siliceous limestone. There are no wholly clastic, or any pure, chemically precipitated limestone in the formation. Considerable clastic material may be found in the lower part of the layer, and almost pure, probably chemically precipitated limestone near the top of the same layer. There is also a considerable lateral lithologic change, and the same layer may show marked lateral facies variation.

*Silty limestone.*—Most of the limestones may be classified as silty limestone, usually gray, ranging from slightly dark, through green, to olive-green, bluish, and light-green hues. Locally yellow or brownish-yellow colors are present, especially in the layers in the oxidizing zone. They contain essentially no carbonaceous matter. The organic material of decaying animals may have limited or prevented the oxidation of ferrous oxides or may have reduced the ferric oxides to ferrous oxides.

The insoluble residue in the limestones ranges from 1.1 to 50.0 per cent with the average content ranging from 15 to 25 per cent. Usually, it is higher in the lower parts of the limestones and diminishes toward the upper part of a single unit, where it tends to increase again forming a transition into the overlying siltstone. There are, however, units in which the insoluble residue content progressively increases toward the top.

The most common insoluble components of the silty limestones are, in order of decreasing abundance: angular and subangular to subrounded grains of quartz; locally, irregular, small aggregates of opal; and iron oxides, present usually as irregularly shaped, powdery aggregates and as a very fine coating on quartz grains. Hornblende (and possibly hypersthene),

galena, flakes of muscovite, and some feldspar are rare. They are disseminated throughout the rock although locally they may be concentrated in thin layers. A few irregular laminae of clay minerals cemented by opal are embedded in limestone.

The silt in the lowermost parts of limestone units may be concentrated into thin laminae of limy siltstone. The limestones that contain less than 10 per cent silty material have a fine crystalline texture. Those that are finely crystalline are dense and break with a conchoidal fracture.

The boundary between limestones and the underlying siltstones is always distinct. The upper boundary, between the limestones and the overlying siltstones, is not so prominent and is transitional. The silt content increases up to 50 per cent in the uppermost transitional part of the units.

The limestone of unit "G" locally is coprolitic. Marine fossils were observed in the silty limestone units throughout the formation. Most of the fossils are very poorly preserved, and many are replaced by calcite.

*Crinoidal limestone.*—This limestone is represented by unit "D" in sections 1, 10, and 12 to 17 (Fig. 4). The limestone ranges from almost white in the most northern locality, section 1, to light-gray in the southeastern sections. The color depends on the amount of insoluble residue. The nearly white limestone of section 1 contains less than 1 per cent, while the residue content in the darker (light-gray) limestones ranges from 3 to about 32 per cent.

The main components of these limestones are broken stems and plates of crinoids, entirely recrystallized. They are well sorted and of a uniform coarse size. A few fragments of thin-shelled terebratulids and aviculopectinid pelecypods are locally present. Like the insoluble residues they increase from the northwest toward the southeast, while the relative abundance of crinoid fragments diminishes in the same direction.

The cement of the crinoidal limestone is calcareous. A few small, irregular cavities have the walls covered by a thin film of iron oxides.

The limestones are massive and do not show bedding, except for a weak indication of cross-stratification in section 15.

The crinoidal limestones of unit "D" were deposited in relatively shallow and clear water, as evidenced by a low amount of silt in the most northern section (1), where the crinoidal content is highest. Apparently the turbidity of the water increased farther south where the limestones of unit "D" contain more silty material suggesting shallower and more turbulent conditions and the proximity of a shore line.

*Oölitic limestone.*—Irregular, thin, oölitic layers of limestone were observed in the upper part of unit "X", in section 16. The limestone is yellowish gray, massive, and very finely crystalline. Large crystals of calcite are disseminated throughout.

The oöids range from oölitic to pisolitic dimensions and show a varied degree of sphericity. Nuclei of the oöids consist of one or more minute crystals of calcite or dolomite. No nuclei of other composition were found in thin sections or on polished surfaces. Concentric growth laminae of most oöids consist of alternating deposits of calcite and dolomite. Many, however, are entirely calcite or dolomite.

Locally, several oöids form small concretions, most of which are spherical, but which may be irregular in shape. The space between the oöids within the concretions is filled with large crystals of calcite. The oöid concretions serve as centers of crystallization and show further concentric aggregation.

The space between adjacent concretions and between concretions and the separate oöids is also filled by large crystals of calcite. The walls of a few cavities are covered by crystals of calcite or dolomite. We do not know what concentrated single oöids into concretions. Neither the oöids nor the concretions show any sign of abrasion or sorting, and oöids of different sizes occur together.

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The insoluble residue, mainly silica, ranges from 1.6 per cent in relatively pure, crystalline limestone to about 30 per cent in distinctly siliceous limestone. The lateral variation of silica is more pronounced than the vertical variation in unit "X".

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A thin section of a cherty concretion from the limestone of unit "S", section 2, revealed a matrix of chalcedony surrounding (1) abundant carbonate in rounded and ellipsoidal grains, pellets, and crystals, some stained black, probably by organic matter; (2) scattered detrital grains of quartz, feldspar, and a few of muscovite; (3) large opaque spots, satiny white in reflected light, that appear to be leucoxene. There is no indication as to what the original titanium mineral was that has altered to leucoxene, or whether the leucoxene

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No fossils were observed in or near concretions. Some of the fossils in the limestone of unit "S" are replaced by chert, but they are not connected with existing cherty concretions

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Gypsum, an important component of the siltstones of the upper part of the Virgin formation, is present in units "$Q_2$", "$T_1$", "$V_1$", "$V_2$", and "W". These units form layers 6 to 50 feet thick, with the thickness increasing from northwest to southeast.

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There are two possible sources for the gypsum:

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The absence of primary structures in parts of the strongly gypsiferous siltstones suggests uninterrupted deposition locally below the wave action. The greater density of lagoonal water caused by evaporation may have modified the waves, so their action was shallower than in the basins containing normal sea water. Small lagoons would also limit the amplitude of waves and diminish their influence on the sediments.

The conditions postulated for formation of the gypsiferous siltstones under restricted arid environment are found in modern lagoons. The classic example is the Gulf of Karabugaz, on the eastern side of the Caspian Sea, surrounded by desert on three sides. The average depth of the gulf is not more than 50 feet. It is separated from the Caspian Sea by narrow sand spits (Grabau, 1920, p. 132). A shallow, narrow (100–500 meters) strait, 5 km long, is the only connection with the Caspian Sea. The current passing through this strait always flows from the Caspian Sea toward the gulf. The current has a minimum velocity 24.5 meters per minute in November and increases to over 44 meters per minute during the summer, when the water level in the gulf falls because of increased evaporation. This stream carries into the gulf a daily load estimated at 350,000 tons of salt.

This gulf represents the extreme case for the formation of gypsum in considerable quantity.

The barrier does not permit the outflow of dense water from the gulf, while hydrostatic equilibrium causes the inflow of the "normal" Caspian Sea water into the gulf. The density of the surface water in quiet basins increases with evaporation, and the heavier water settles. Gypsum will precipitate from solution when the salinity increases to 3.5 times the normal concentration of sea water, at or near 30°C. The precipitation will continue until the salinity reaches approximately 4.8 times the normal salinity of sea water. Beyond this point the calcium sulfate will be precipitated as anhydrite. Hydrogen-ion concentration (pH) required for precipitation under restricted arid environment is 8 to 9. The pH value of the Caspian Sea ranges between 7.6 and 8.6 (von Raupach, 1952, p. 92). The pH increases with increasing salinity.

When gypsum was precipitated in the upper part of the Virgin formation, fine particles of clay or silt were being transported by wind or water into the depositional basin and may have formed nuclei for the precipitation of gypsum. The primary coating on silt grains is responsible for the "red" gypsiferous siltstones. The cement is hydrous calcium sulfate and calcium carbonate.

The association of gypsum with calcium carbonate has been noted by McKee (1938, p. 123) in Toroweap alpha, facies 1, from Hilltop, near Havasu Canyon, Arizona. There the gypsum is not replacing the limestone but fills fractures and cavities in older limestone.

In the gypsiferous siltstones of the Virgin formation, gypsum is the dominant mineral of the matrix. The gypsum did not replace the limestone, and it seems certain that gypsum and calcite were precipitated contemporaneously.

The association of calcium carbonate and gypsum has been briefly considered by Stieglitz (1909), Pia (1932), and others. Their conclusions are summarized below.

Considering a solution in which gypsum and calcite are in equilibrium the following formulae are obtained:

$$CaSO_4 \rightleftharpoons Ca^{++} + SO_4^{=}$$
$$CaCO_3 \rightleftharpoons Ca^{++} + CO_3^{=}$$

The constants of the ionic product (or dissociation) of a solution saturated with gypsum and calcium which are in equilibrium may be expressed:

$$[Ca^{++}]\cdot[SO_4^{=}] = ks \text{ (constant for S)}$$
$$[Ca^{++}]\cdot[CO_3^{=}] = kc \text{ (constant for C).}$$

The valence of $Ca^{++}$ in both equations is the same, but the required amount of $Ca^{++}$ ions is much greater in calcium sulfate than in calcium carbonate (Pia, 1932, p. 20). From the equation

$$[SO_4^{=}]:[CO_3^{=}] = ks/kc$$

it may be calculated that the amount of sulfate ions in solution must be "about 5000 times greater" (Pia, 1932, p. 20); 4700 times greater (Stieglitz, 1909, p. 250) than that of carbonate ions, in order to maintain the equilibrium.

Under natural conditions the excess of sulfate ions is not so great as required to maintain the equilibrium. Thus, the carbonate precipitates first until the concentration of carbonate ions reaches a ratio 1/5000 that of the sulfate ions (the ratio ks/kc).

When in the solution, which is in equilibrium with both salts, the concentration of the sulfate ions is increased by an addition of a second sulfate (sodium or potassium sulfate), the solution is oversaturated with calcium sulfate and gypsum precipitates. The loss of calcium ions makes the solution undersaturated in regard to the carbonate, and some of the calcium carbonate present must pass into solution until the ratio 1/5000 is reached (Stieglitz, 1909, p. 251). Generally, calcium carbonate precipitates first as pure calcite until the conditions of equilibrium are re-established, and then, with advanced evaporation, a mixture of both calcite and gypsum precipitates.

A precipitation of a mixture of two minerals from solution is theoretically and practically possible (Findlay, 1900, p. 416–417). Under certain circumstances only an easier soluble salt may be precipitated. The separation depends on the constants of equilibrium.

Von Raupach (1952, p. 113) states that in Karabugaz-göl a layer 1 mm thick of sulfate-carbonate sediment is deposited yearly and that the solubility constants of carbonates and sulfates are influenced by the water temperature; sulfates precipitate in winter, and car-

bonates in summer. The yearly banding of the sediments, however, is not due to the turbidity of water. This raises the question of whether temperature may not be more significant than hydrogen-ion concentration in explaining the apparent simultaneous deposition of gypsum and calcite.

The occurrence of calcium carbonate with gypsum, as the cement in siltstones of the Virgin formation, points to a restricted arid environment of deposition, where evaporation exceeded precipitation and inflow. As the evaporites are represented mainly by primary gypsum, and only locally by small percentages of anhydrite, the prevailing temperature during deposition must have been around 30°C, and only occasionally, and then for short periods, above 30°C, when anhydrite precipitated. The very high salinity in the basins limited or even inhibited organic life, and the evaporites were precipitated from saturated solution in the absence of bacteria or higher organisms.

The lagoons did not need to be connected with the open sea, but occasional influx of sea water is possible and may have influenced the equilibrium and solubility of the gypsum and calcite.

During the deposition of the siltstones "$Q_2$", "$T_1$", and "W", environmental conditions did not undergo major changes. Owing to migration of the shore line, the distance of the depositional basin from the sea varied during the deposition of the siltstone of unit "$V_3$". Lenticular conglomeratic layers of fragments of gypsiferous siltstones are embedded in silty gypsum. These layers, marking diastems, may have been formed during storms.

## Sedimentary Structures

### *Bedding*

The stratification of the limestones ranges from shaly to massive. Some of the crystalline limestones are essentially structureless, showing a thin bedding only on weathered surfaces. Most silty limestones exhibit finer bedding than do the less silty ones, and most of the limestones have irregular and uneven bedding. Regularity of bedding seems to be an exception.

The siltstones generally exhibit a uniform shaly and flaggy bedding. A single stratum may range from less than a fraction of an inch to 1 foot 4 inches thick. The bedding of calcareous, gypsiferous siltstones is not well developed; the weathered rock does not show bedding and crumbles very readily. Other weathered siltstones split easily along the bedding planes into thin layers.

### *Cross-Stratification*

A few layers of limestone "A", "C", and "S" are cross-stratified in several localities. Cross-stratification seems to be normal in the uppermost limestone layer of unit "C". This clastic limestone is composed mainly of fragments of fossils. In many localities "torrential" cross-strata dip up to 23° with respect to the original horizontal surface. This limestone may have been built by the action of marine current, much as delta deposits are formed today—the current carrying the shells and their fragments from the shore and depositing them on the consecutively built foreset slopes.

A fine cross-ripple lamination was developed locally in limestones containing interference ripple marks.

Cross-bedding in the siltstones is rare and occurs chiefly on a small scale in association with ripple-marked surfaces (cross-ripple lamination).

### *Graded Bedding*

Graded bedding is common in the gray, calcareous siltstones. These are thinly bedded or laminated, and the bedding is marked by the decrease in size of silt grains from the bottom toward the top of a single lamina.

### *Ripple Marks*

Ripple marks are present on the tops of many siltstones. They are less well developed in the limestones but, where present, they are conspicuous among the primary structures. This is notably the case in units "S", "U", and "V".

Ripple marks are essentially limited to parts of the limestone with considerable silty material and to limestones that are laminated or that have a shaly bedding.

Oscillation ripple marks in the silty lime-

stones of unit "S" probably result from the wave action and are the most persistent ripple marks observed.

Ripple marks in the silty limestones of "U" and "V" are asymmetrical and are interference ripple marks. They were probably built by cross currents or by interaction of waves and currents with the latter currents partly obliterating earlier ripple marks.

A few *Pleurophorus*, and some indeterminate, irregular, tubular forms resembling worm trails, are associated with ripple marks in the limestone of unit "U".

Ripple marks on the top surfaces of most of the siltstones have amplitudes of less than 1 inch. Most are poorly preserved, but molds developed on the lower surfaces of the overlying limestones show that they were formed both by wave- and current action.

### *Mud Cracks*

Mud cracks were observed only in the limestones "A", in sections 1 and 12, and in the limestone "L", in section 6. The layers in which the mud cracks occur are silty near the bottom, and both grain size and silty material diminish toward the top.

The mud cracks in the limestone "A" in section 1 are arranged in an irregular, polygonal network. The cracks are up to 4 inches deep and, where bedding is thin, may affect more than one layer. The cracks range up to 1 inch wide at the top, wedging downward, and are filled by the dark-gray limestone from above.

The mud cracks on the top of limestone P-529 represent a very delicate network. The crack reticulation is very shallow and narrow, but conspicuous.

Mud cracks occur near the top of many siltstones. They are well preserved in only a few places and are not easily detected.

### *Submarine Denudation*

On all exposures of the top of the uppermost limestone of unit "C" a series of parallel grooves trend north-northwest. The grooves are unevenly spaced and are up to 2 inches from crest to trough. In places they are more than 10 inches apart but locally they are crowded. They appear to be parallel. Many striae parallel the grooves. The surface resembles the markings of a fault plane. However, such a fault would have had to occur along an almost horizontal plane, and there are no indications of such a bedding-plane fault.

The writer believes that these grooves and striae result from submarine slumping, before complete induration of the sediments. The slumping may have been started by turbidity currents, the gravity of the sediments, or by an earthquake. Once the equilibrium had been upset, the mass of the sediments would glide over a submarine slope, until it came to rest upon a horizontal sea bottom, or until the turbidity currents that may have been started by the slumping had picked up most of the material from the bottom. This material may be redeposited in the same area or may be transported and redeposited elsewhere.

It seems unlikely that a turbidity current transporting sediments could have formed the grooves. At least they would not have produced parallel grooves over distances observed on the top of the limestone of unit "C". The grooves may have been gouged during submarine slumping of partly solidified muds over the sediments. Heim (1908, p. 142) applied a term "Subsolifluktion" to the sliding of subaqueous sediments. This term was a modification of "solifluction" coined by Andersson (1906, p. 96) in his discussion of subaerial denudation. Heim noted that subaqueous solifluction may occur on slopes with an inclination as low as 2°–3°, although it is most frequent on slopes between 4.4° and 6.0°.

Rettger (1935, p. 276) deformed soft sediments by slump, differential movement, and differential loading. He showed that the mass will begin to slide when the tank is tilted about 7° from horizontal, but in several instances the required gradient was as much as 20°.

Heim (1908), studying subaqueous slumps in the lakes of Switzerland, concluded that "the greater the moving mass (of mud) the smaller the average inclination of the slope" (p. 142) required to start and continue the movement.

The crinoidal limestone of "D" was deposited on bevelled surfaces of the cross-stratification

of "C". The limestone of "D" is missing in sections 3 to 9, and 11, possibly because of "omission" resulting from subaqueous solifluction, or because of subaqueous "dereption." Heim (1924, p. 5) applied the term "omission" to a period of nondeposition and "dereption" to subaqueous denudation by mechanical action of water currents.

It has been impossible to recognize in the field sediments transported by slumping, unless they are represented by the strata that overlie the limestone "C". The crinoidal limestone of "D" that locally overlies the limestone of "C" argues against the foregoing hypothesis. If the crinoidal limestone had slumped, more silty or clayey material would be expected in it.

The most striking example of contorted bedding is an intricate "folding" in siltstone of "P". This greenish-gray unit is composed mainly of quartz grains of medium silt size, cemented by a moderate amount of lime. Many layers of "P" apparently were exposed above the water level for short periods, at least. They contain indeterminate tracks and "shell-and-cast" structure, developed probably during differential desiccation. These structures could have been preserved only where they were covered by silt deposited in quiet water.

The similarity of the structures in "P" to the structures of deformed strata described from other parts of the world and from other formations, by Heim (1908; 1924), Fairbridge (1946), and Kuenen (1948; 1950a; 1950b; 1951) supports the supposition that subaqueous slumping has caused this deformation.

### *Intraformational and Basal Inclusions*

Small, scattered fragments of greenish-gray, yellow-gray, and gray calcareous siltstone are included in the basal parts of several limestone units. They vary in size and shape, are commonly subangular and angular, but some are irregular. They range up to 4 inches in diameter, but the average is less than 1 inch.

The inclusions are locally concentrated along the bedding planes and also occur near the top of the same layer (limestone of unit "L", section 3). The inclusions have been derived from the siltstones directly under the limestones, and the fragments may have been transported but a short distance before being emplaced in limestones.

Siltstone fragments near the bottom of the limestone units, and also ripple marks and mud cracks on the top of the underlying siltstones indicate diastems or intraformational disconformities.

The origin of the siltstone fragments included in the middle part of the limestone, such as the limy siltstone inclusions and those on the bedding planes of limestone units (as in unit "L", section 3), is not certain. The fragments of siltstone may have been rafted on algal holdfasts or in roots of trees, and transported by sea currents into areas of limestone precipitation.

### *Concretions*

In the middle of limestone "A" in section 12 are lenticular concretions of silty limestone, slightly lighter in color than the enclosing rock. These concretions occur in the cross-stratification of the bed.

Other concretions, spherical to almost round, occur in the upper part of the limestones of unit "C", in sections 14 and 17. These range in diameter from 4 inches to 2 feet and are gray, dense, hard, finely crystalline limestone. They occur within a massive limestone layer. The concretions may be recognized by differential weathering on the upper surface of the limestone.

Concretions of various sizes and shapes are present in most of the gray siltstones. They consist of limy siltstone, usually much harder than the surrounding rock, or of silty limestone. The most common are disc-shaped, about half an inch thick, and 1–2 inches in greatest diameter. The bending upward of the laminae in the siltstone around the concretions suggests that they are syngenetic.

Other concretionlike bodies consist of lenticular layers of silty limestone that may have developed as rows of platy concretions united to form a continuous layer.

### *Stylolites*

Stylolites are limited to limestones containing relatively little silty material and having a

finely or coarsely crystalline texture. They are common in several of the limestone layers of "A" and in some of the layers of "C". The limestones of "S" and "X" also contain stylolites locally.

The stylolites occur usually within single limestone layers. In section 15 stylolites occur between layers at the contact of the limestone of unit "C" with that of unit "D". All have up to 4 inches of vertical relief. The space along the stylolites is filled by clayey limestone "residue" that ranges from 3 to 8 mm thick.

All stylolites observed parallel the bedding. They probably were formed after the consolidation of the rock but before structural deformation. There is no evidence for a syngenetic formation of stylolites.

### Cyclic Sedimentation

A repetition of strata is interpreted as a form of cyclic sedimentation, as defined by Weller (1930). Individual cycles in the Virgin formation consist of an alternation of limestone and siltstone. A single cycle is bounded both below and above by an unconformity.

Sea waters are believed to have encroached over broad coastal plains creating favorable conditions for precipitation of limestone. Silty limestones, locally containing inclusions derived from the underlying siltstones, were deposited first. When the turbulence subsided, nearly pure limestones were precipitated. These pure limestones grade upward into very silty limestones that form transitions between the two types of sediment. The influx of silty material continued to form siltstones until the basins were filled. The upper surfaces of siltstones show either subaqueous denudation or subaerial weathering or erosion. With invasion of the sea, a new cycle of deposition began.

Four complete cycles were observed in the lower part of the formation. The lithologic variation appears to be mainly a function of the amount of silt deposited. During periods of no silt deposition, relatively pure limestones developed; as silt influx began and increased, the limestones became more silty until the rock became a calcareous siltstone. In late stages, the silt influx appears to have exceeded the rate of the sinking of the basin of deposition, so that the basin became filled. Most probably, by-passing (Eaton, 1929, p. 714) and nondeposition were important factors. During this interval evidences of erosion suggest diastems of unknown time significance.

The cause of the variation in silt content and hence the reason for cyclical deposition is not known. According to Wanless and Shepard (1936) it may be due to (1) periodicity of tectonic movements, (2) climatic cycles of various lengths, (3) sea-level fluctuation, (4) cyclical shifting of the distributaries of a delta, and (5) periodic volcanism. The last two may be disregarded here for no evidence of deltaic sedimentation or of volcanic activity is available. However, the other causes may have influenced the cyclic sedimentation.

The alternation of silty limestone and calcareous silts with a slight disconformity at the base of limestones, and the lenticular and tabular bodies indicate a neritic type of cyclic sediments (Wanless and Shepard, 1936, p. 1186) and suggest a foreland condition of deposition on a mildly unstable shelf.

### Paleontology

Marine fossils occur in the gray, calcareous siltstones and in the limestone units of the formation. Most of them are very poorly preserved. The best preservation is among large specimens of *Aviculopecten*, but they, as well as most of the other fossils, could be determined only to genera. Most of the fossils in the crystalline limestones are replaced by calcite.

CRINOIDS: Crinoid stems and calyx plates and echinoid spines are in almost every limestone and in many siltstones. Some limestones are almost entirely crinoid fragments (unit "D"), and the fragments form the bulk of the limestones of units "G", "J", "N", "S", "X", and, locally, "L". No complete calices have been found. Girty identified the crinoid fragments collected by Reeside and Bassler (1922, p. 67) as *Isocrinus*.

Crinoids may indicate the depth and temperature of the environment. Crinoids live in temperatures between 25° and 85°F, from very shallow water to the greatest depths, and

in any latitude (Clark, 1931, p. 26–28). However, the family Pentacrinidae, to which the crinoids in unit "D" may belong, require temperatures from 55° to 65°F. This temperature appears to be most convenient for their physiological and ontogenetic development (Clark, 1914, p. 10).

Temperatures ranging from 55° to 65°F are found down to the depth of about 125 fathoms (Kuenen, 1950b, p. 25). Thus, the Virgin formation crinoids may have lived in any depth above 125 fathoms.

BRACHIOPODS: Two groups of brachiopods have been noted in the limestones. Both are relatively well preserved because of their phosphatic shells.

The superfamily Triplesiacea is represented by a form "Pugnax," strongly resembling the genus *Pugnoides*. They are common or abundant in limestones with a small amount of clastic material, units "A", "C", and "G", but are considerably less abundant in units "L" and "N". They were not observed above "N".

A second group belongs to the superfamily Terebratulacea. Specific identification has not been made. These brachiopods are rare to common in the limestones of units "A", "C", "E", and "G" and are abundant in the silty limestones of units "L" and "N". They are especially abundant in the limestone of unit "U".

PELECYPODS: Pelecypods are present in almost every silty marine stratum but were not observed in the lagoonal facies. They are very rare in the crystalline limestones and especially abundant at the top of the silty limestones, notably unit "G", and in limestone layers of unit "V", where they form the bulk of the rock.

In the transitional zone between the limestones and overlying gray siltstones, there is in many places a layer of limy siltstone, 4–8 inches thick, in which large pelecypods, including *Aviculopecten*, are common.

The poor preservation of pelecypods has prevented their specific identification, and their generic identification is only tentative.

The fauna in the limestone units contains large specimens of *Aviculopecten*, *Myalina*, and *?Pseudomonotis*. The smaller pelecypods are represented by *Monotis*, *Bakewellia*, *Pleurophorus*, *?Myophoria*, and dwarfed (?) forms of *?Pseudomonotis* and *Myalina*.

The gray, calcareous siltstones contain many small pelecypods which form about 95 per cent of the fauna in units "F", "I", "O", "Q", and "V". No fossils have been observed in siltstones of units "B" or "T". *Monotis*, *Myalina*, *Pleurophorus*, and *?Pseudomonotis* persist in siltstones of units "F" to "O", while *Bakewellia* is known only from siltstone of unit "F".

GASTROPODS: Preservation of the gastropods is even poorer than that of other fossils. Two forms that may be *Pleurotomaria* and *?Naticopsis* are in the near-shore limestones of the upper part of the formation. A very small gastropod, resembling a small *Valvata*, occurs in the near-shore siltstones of the upper part of the formation.

WORMS: Small, calcareous worm tubes that may be *Spirorbis* have been noted in strata that represent a shallow, marine, near-shore environment. Worm tubes locally are attached to the shells of large *Aviculopecten*. Worm trails of other types occur on top surfaces of the siltstones of probable tidal-flat origin.

CRUSTACEANS: About 3 feet above the base of the siltstone of unit "Q", in section 3, small, poorly preserved crustaceans occur in association with small gastropods (*?Valvata*) and some small, indeterminate pelecypods.

Dr. Leif. Størmer of the Paleontologisk Institut Styrer in Oslo, Norway, has identified these crustaceans as *Halicyne*. *Halicyne* has been figured by Woodward (1866–1878), as *Halicyne*, von Meyer, 1847 ("Paleontographica," vol. 1, p. 134) under the name *Halicyne agnota*, and a second species under the name *H. laxa*. *Halicyne laxa* has been collected in the Muschelkalk (Middle Triassic) of Rottweill in Germany.

Ostracods are abundant in some of the calcareous siltstones. They are poorly preserved and have not yet been studied carefully.

CEPHALOPODS: Poorly preserved, fragmentary cephalopods belonging to the subclasses Nautiloidea and Ammonoidea were collected in the lowermost 7 feet of the siltstone of unit "I". All the specimens were collected north of section 14.

The Ammonoidea were examined by Dr.

Siemon Wm. Muller, and most of the specimens were identified as *Tirolites spinosus* Mojsisovics *s. l.* Two specimens were identified as *?Cordillerites* and possibly *?Hungarites*. Regarding *Tirolites spinosus*, Muller observes that "all these species characterize the top of the Werfener beds in the Alps or the top of the Lower Triassic." The other two ammonoids, *Cordillerites* and *Hungarites*, are also characteristic of the upper part of the Lower Triassic.

The Nautiloidea are represented by orthoceratids and are not diagnostic as to the age.

## Age and Correlation of the Virgin Formation

The ammonoids—*Tirolites spinosus* Mojsisovics *s. l.*, *?Cordillerites*, and *?Hungarites*—collected during the present study are the only fossils that indicate the age of the Virgin formation.

The Lower Triassic of North America is divided by Smith (1932, p. 13) into the following ammonite zones:

V. *Columbites* zone
IV. *Tirolites* zone
III. *Meekoceras* zone
II. *Genodiscus* zone
I. *Otoceras* zone.

*Tirolites* in strata about 107 feet below the top of the Virgin formation places the formation definitely in the upper part of the Early Triassic and clearly suggests that some, at least, of the overlying "members" of the Moenkopi group are Middle Triassic.

The only place in the United States where *Tirolites* has previously been found is Paris Canyon, Bear Lake County, Idaho. The *Tirolites* zone there is about 225 feet above the *Meekoceras* zone and 30 feet below the *Columbites* zone (Smith, 1932, p. 18). Kummel (1943, p. 322) confirms the conclusions of Smith.

The *Tirolites*-bearing strata of the Virgin formation appear to be correlative with the *Tirolites* limestone of the Thaynes formation in the Bear Lake area of southeastern Idaho. They also may be correlated with the Campil beds of Tyrol (Smith, 1932, p. 18; Mojsisovics, 1882, p. 64–75) and with upper Werfener strata of the other Mediterranean localities of the Triassic provinces (Kittl, 1903, p. 1–10).

## Depositional History of the Virgin Formation

The lithology, sedimentary structures, and stratigraphic sequence of the Virgin formation permit the following interpretation of its depositional history.

Post-Kaibab, pre-Moenkopi warping and erosion formed deep valleys in the gypsiferous siltstones and the limestones of the alpha member of the Kaibab formation. The two lowest "members" of the Moenkopi group in the St. George area—the Timpoweap "member" and the lower red "member"—were deposited on this eroded surface. The Rock Canyon conglomeratic strata filled channels, some of which were 250 feet deep (Reeside and Bassler, 1922, p. 60), in the Kaibab limestone.

The siltstones of the lower red "member" of the Moenkopi group were deposited apparently without break in sedimentation on the Rock Canyon conglomeratic "member" and, locally, on the gypsiferous strata of the alpha member of the Kaibab. These siltstones, which appear to have been deposited under lagoonal conditions, may have covered the gypsiferous alpha member of the Kaibab.

After deposition of the lower red "member" erosion developed a topography characteristic of late maturity. Locally, channels may have been cut through to the alpha member of the Kaibab.

The Virgin formation formed as the sea advanced to develop relatively quiet embayments across the extensive rolling topography of the lower red "member." Lensing, and a lack of uniform thickness in single strata of the lower portion of unit "A", are a result of the uneven surface upon which they were deposited.

The absence of a basal conglomerate and the presence, in its place, of considerable clastic material in the lowermost limestone stratum of unit "A" suggest that only well-weathered regolith was present on the erosion surface and that the surrounding lands were low and deeply weathered, furnishing little coarse debris. The presence of only scattered, angular, and subangular fragments of the lower red "member" as inclusions in the basal stratum of unit "A" suggests that wave action in the

advancing sea was not sufficiently strong to do much more than rework the regolith and did not seriously attack the unweathered deposits beneath it.

Occasional mud cracks on some of the lowermost limestone strata of unit "A", and local cross-stratification of deltaic type, also confirm that the sea advanced as very shallow embayments over a relatively flat surface. Slight elevations on this surface may have limited the embayments and deflected currents and waves sufficiently to cause the cross-stratification. The mud cracking probably was caused during low tides when the sea withdrew from extensive areas of the shallower embayments.

Subsidence appears to have been slow but continuous, and by the time the lower half of unit "A" had been deposited the irregularities of the initial basin of deposition had been buried. The persistence of the upper part of the unit testifies to the regularity of the floor of deposition, and the lack of silt indicates deposition in clear waters.

The clear, quiet waters permitted the immigration and development of terebratulid brachiopods. Percival's studies (1944) of recent *Terebratella* have shown that they require relatively quiet waters and a firm substratum, covered only with a thin film of organic debris for feeding.

The fragments of crinoids in the limestones of a part of unit "A" containing brachiopods support the theory of quiet water. The crinoids probably did not live far from the place of burial.

During the deposition of the siltstone of unit "B", an influx of clastic material filled the depositional basin to base level. The surface of the siltstone was exposed to waves and currents, as evidenced by the interference ripple marks and by local erosion. This ended one cycle of deposition.

A new cycle began with the deposition of the limestones of unit "C". The lowermost limestones contain considerable silt. This may have been derived from the reworking of the uppermost layers of unit "B" or may have come from a source outside the basin.

The silt content diminished rapidly with the progress of sedimentation, and limestones of the upper part of unit "C" contain only scant silty material. The limestone directly below the top layer contains abundant fragments of crinoids. This limestone is strongly cross-stratified, showing "torrential" cross-bedding. It may have been formed from crinoid fragments driven by sea currents and deposited on a slightly inclined slope of a shallow sea floor, similar to the way deltas are built.

The upper surface of the limestone of unit "C" is grooved and striated. These grooves may have been formed by sliding of overlying, not entirely consolidated sediments. It is not possible to determine what strata, if any, are missing. The sediments may have been transported a long distance.

Subsequent to the grooving of the upper surface of unit "C" there was a period of little influx of detrital material when the crinoidal limestone of unit "D" was formed. Such a limestone required clear sea water and the action of waves or currents to transport and sort the material.

The increase of silty material in the limestone of unit "D" to the southeast suggests that the source must have been in that direction.

Renewed influx of detrital silty material resulted in the deposition of unit "F". The laminae of the siltstones show a slightly graded bedding, suggesting possible seasonal changes controlling the influx of clastic material.

The increase in lime and in the thin layers and laminae with ripple marks toward the top of the unit "F" and mud cracks on the top of the uppermost siltstone indicate a shoaling of the depositional basin and exposure to atmospheric action, probably as tidal flats. The occurrence of fragments of this unit in the lowermost limestone of the overlying unit "G" testifies to slight erosion of the exposed surface of unit "F" before the deposition of unit "G".

The thin, chemically precipitated, lowest limestone of unit "G" indicates that a third cycle began with an influx of clear marine water. Overlying the basal, essentially nonsilty layer are very silty limestones. Wave action left ripple marks on the uppermost surface.

During the deposition of the limestones of unit "G" the amount of silty material increases in some places from the bottom to the top of a single layer, while in other localities the lower part of the same layer contains more silt than its upper part.

Conditions during the deposition of the siltstones of unit "I" were very similar to those of "F". In addition to a dwarfed pelecypod fauna, a few cephalopod genera (*Tirolites*, *?Cordillerites*, *?Hungarites*, and some *"Orthoceras"*) inhabited this area during the deposition of the lowest part of the siltstones.

Near the end of the deposition of the siltstones of unit "I", thin layers of silty limestones were deposited locally. The depositional basin was again almost filled as evidenced by interference ripple marks.

A difference in thickness of the siltstones of unit "I" in various localities may have been caused by an uneven distribution of silty material during deposition, by varying erosional conditions at the end of deposition, or by slight post-depositional tectonic movements. There is no field evidence for any crustal movements, and the other hypotheses seem more likely.

Units "L", "M", "N", and "O" represent a fourth depositional cycle. This cycle differs from those below in that silt influx early in the cycle resulted in the highly calcareous siltstone unit "M", rather than silty limestones, such as in unit "G". The limestone of units "L" and "N", underlying and overlying "M", represents the normal, basal facies of the typical cycle.

The vertical and lateral variation in silt content in the limestones of "L" and "N" indicate local variation of the turbidity of sea water. This may be due to the uneven distribution of silty material either by streams or by sea currents.

The local abundance of crinoid fragments and terebratulid brachiopods in the crystalline parts of the limestones "L" and "N" indicates quiet but relatively shallow water. Pelecypods —mainly *Myalina*, *Monotis*, and *Pseudomonotis*—are rare in the crystalline limestones but increase in the silty limestones of the same unit.

An influx of silt near the end of deposition of limestone "N" marks the transition to unit "O".

Rhythmic, graded bedding in the laminated siltstones of unit "O" suggests seasonal (?) changes that affected the influx of silty material. Common ripple marks indicate shallow-water conditions for the lower part of the siltstones. Generally, silt increases gradually toward the top of the unit, where most of the deposits are laminated. The absence of ripple marks suggests quiet-water deposition.

Indeterminate tracks and raindrop imprints on the top of the uppermost siltstone of unit "O" indicate that at the end of the siltstone deposition the basin must have been filled. Withdrawal of the sea locally exposed the sediments to atmospheric action.

Cyclic sedimentation characterizes all the deposits through unit "O". Another cycle started with the deposition of the limy siltstone of unit "P". Unit "P" clearly demonstrates changing conditions in the source area and to some extent forecasts changes in the depositional basin that control the nature of the overlying units "Q", "$Q_1$", and "$Q_2$".

The siltstones of unit "P" are highly calcareous and show rhythmical alternation of thin beds and laminae of fine with somewhat coarser-grained siltstone. Locally, the strata are cross-ripple laminated, and diastems are numerous.

The siltstones of unit "P" are very contorted, strongly folded, and intricately crumpled by preconsolidation slumping. The deformation of the layers persists throughout the area. The underlying and overlying strata have not undergone similar deformation.

The siltstones of unit "P" clearly suggest shallow-water deposition with possible seasonal variation controlling the size distribution and amount of silty material entering the basin. Worm trails and raindrop imprints indicate that the top of the siltstone was exposed to subaerial weathering, probably as tidal flats.

The siltstones of units "Q" and "$Q_1$" are only in sections north and northwest of section 11. In section 11, and in all sections to the southeast, the gypsiferous siltstones of unit "$Q_2$" replace them in the sequence.

The abrupt change in lithology indicates that a barrier, probably a sand bar, was formed

directly north of section 11. This bar resulted in the formation of lagoons to the southeast. The water in the lagoons was subject to excessive evaporation, resulting in the precipitation of gypsum in the beds. Northwest of the bar, however, shallow marine conditions persisted during the deposition of unit "Q" and "$Q_1$". "Red" coloration of the siltstones of unit "$Q_1$" suggests deposition under conditions that permitted at least partial oxidation of ferrous oxides. The coprolitic siltstones of unit "R", known only from section 1, were also deposited in shallow sea.

A disconformity at the top of the coprolitic siltstones of unit "R" in section 1, at the top of the siltstones of unit "$Q_1$" in section 2 to 8, and at the top of the siltstones of unit "$Q_2$" in sections 11 and 12 suggests extensive erosion.

Renewed subsidence of the depositional basin resulted in a southeastward migration of the bar to a position slightly to the north of section 14. At the same time the typical sedimentary cycles were again initiated in the marine areas of deposition. The basal calcareous strata of the new cycle are represented by crystalline limestones of unit "S". These limestones contain a considerable amount of crinoid fragments and a small amount of silty material which indicate shallow, clear, and warm-water conditions.

The overlying siltstone of this fifth cycle is represented by the siltstones of unit "T". As these filled the basin, the bar shifted again, for a short period, to a position north of section 11.

A new, slight subsidence again caused the retreat of the bar, and the limestone of unit "U", in the sections north of 14, and siltstones with the thin layers of limestone, unit "V", were deposited.

As this cycle was completed with the filling of the basin, the shore line migrated northwest, and gypsiferous siltstone (unit "$V_1$") was deposited. The sediments indicate arid conditions.

Local conglomeratic lenses, unit "$V_2$", indicate that the basin was filled at the end of the fifth cycle and subject to erosion.

The limestones of unit "X" overlying the gypsiferous deposits throughout the whole region represent the final marine invasion of the area. These limestones suggest chemical precipitation. Crinoid fragments, locally present, point to shallow, warm-water conditions.

A general emergence, or a much increased rate of sedimentation, caused the sea to withdraw toward the west or northwest. This marked the end of deposition of the Virgin formation in the area and initiated the sedimentary environment in which the middle red "member" of the Moenkopi group was deposited.

## Description of Selected Measured Sections

| Unit | | Thickness (Feet) |
|---|---|---|
| | *Section 1* | |
| | Top of hill; recent erosion surface | |
| | Virgin formation: | |
| S | Limestone, P-449, gray and yellowish gray; locally siliceous; beds 1–4 inches; alternating with calcareous siltstone laminae; silicified fossils | 5.3 |
| | Limestone, light gray; silty, laminated and cross ripple-laminated; disc-shaped cherty concretions up to ½ inch in diameter | 1.6 |
| | Limestone, P-448, light gray, silty, shaly; finely cross-laminated; beds up to 2 inches thick; alternating with calcareous siltstone, yellow gray; beds up to 1 inch thick; calcareous siltstone inclusions up to ½ inch in diameter at base | 2.0 |
| | Disconformity: no relief | |
| R | Siltstone, P-443-446, yellow gray; slightly calcareous; coprolitic; laminated; porous; small gastropods | 2.3 |
| | Siltstone, yellow gray; slightly calcareous; laminated and cross ripple-marked; alternation of hard and soft beds ½ to 2 inches thick | 10.0 |
| | Siltstone, P-442, brown and yellow gray; slightly calcareous; laminated; molds of indeterminate pelecypods | 2.3 |
| | Disconformity: contact flat, no relief | |
| $Q_1$ | Siltstone, P-441, brownish dark gray; slightly calcareous; laminated, ripple-marked; yellow-gray siltstone laminae near the top | 18.6 |
| P | Siltstone, P-440, gray, greenish gray; calcareous; laminated and flaggy; locally ripple-marked; middle part of unit crumpled and contorted owing to subaqueous slumping; indeterminate pelecypods, worm trails, raindrop imprints | 9.2 |
| O | Siltstone, P-92-94, gray to dark gray; | |

| | | |
|---|---|---|
| | calcareous; weakly laminated; poorly preserved pelecypods, ostracods | 10.6 |
| N | Limestone, P-439, greenish gray; very silty; abundant *Aviculopecten, Myalina, Bakewellia* | 0.2 |
| | Limestone, P-438, dark gray; silty near the top; brachiopods, pelecypods; crinoid fragments | 0.8 |
| | Limestone, P-436-437, gray to yellow gray; laminated to flaggy; angular and subangular siltstone fragments near the top and at the base; inclusions up to 4 inches in diameter; abundant crinoid fragments, indeterminate pelecypods and brachiopods | 1.6 |
| | Disconformity | |
| I | Siltstone, P-80-86, 433A-435, gray and brownish gray; calcareous; the uppermost 2 inches not calcareous; laminated, and cross ripple-laminated; thin, irregular lenses of silty limestone; pelecypods and small gastropods near the top; *Tirolites spinosus* Mojs. *s. l.*, *?Cordillerites, ?Hungarites, "Orthoceras"* in the lowermost 6 feet; ostracods | 42.0 |
| G | Limestone, P-75, light olive green; silty; crinoid fragments, *Aviculopecten, Bakewellia, Myalina*, worm trails | 0.3 |
| | Limestone, P-76, gray; finely crystalline; near the bottom silty and with silty limestone inclusions up to 1 inch in diameter; very fossiliferous | 0.5 |
| | Limestone, P-77, gray, thin, irregular beds; many fossils replaced by calcite | 0.7 |
| | Limestone, P-78, 431, gray, slightly silty; massive; abundant crinoid fragments; few mollusks; stylolites 2 inches below the top | 2.3 |
| | Limestone, P-79, 432, gray; crystalline; massive; weathers into "concretions" | 0.8 |
| | Disconformity | |
| F | Siltstone, P-430, gray, dark gray; calcareous; with irregular lenses of silty limestone; ripple marks, interference ripple marks at the top; poorly preserved *Monotis, ?Pseudomonotis, Bakewellia, ?Pleurophorus*, worm trails | 50.0 |
| E | Limestone, P-457, yellowish gray; silty, grades into overlying siltstone P-430; crinoid fragments, small gastropods common; pelecypods and brachiopods common to rare | 1.6 |
| D | Limestone, P-455, crinoidal; light gray to white; massive; indeterminate mollusks; overlying the bevelled limestone P-456 | 3.0 |
| C | Limestone, P-456, gray; dense, crystalline; "torrential" cross-stratification· | |
| | single bed 6 to 12 inches thick; upper surface bevelled; abundant crinoid fragments; indeterminate pelecypods, locally terebratulids and *"Pugnoides"* common | 4.6 |
| | Disconformity: here covered by talus | |
| B | Slope covered by talus | 17.0 |
| A | Limestone, P-453-454, gray; crystalline; massive; many stylolites; crinoid fragments, and indeterminate pelecypods and brachiopods | 6.4 |
| | Limestone, P-452, gray; crystalline, with silty laminae; bedding irregular; mud cracks at the top | 1.6 |
| | Limestone, P-451, light yellow; crystalline, locally silty; laminated and ripple-marked | 0.8 |
| | Limestone, P-450, light gray and gray; siltstone inclusions up to 4 inches in diameter; satinspar in veins | 0.6 |
| | Unconformity: moderate relief of surface | |
| | "Lower red member" of Moenkopi group | |

*Section 3*

| | | |
|---|---|---|
| | Top of hill; recent erosion surface | |
| | Virgin formation: | |
| S | Limestone, P-72, gray; dense, crystalline; crinoid fragments abundant | 1.3 |
| | Limestone, P-71, light green gray; dense; indeterminate fossils near the top | 0.6 |
| | Limestone, gray and olive gray; silty; massive; showing lamination on weathered surface; ripple marks on top; indeterminate mollusks | 5.3 |
| | Limestone, yellow gray; silty | 0.6 |
| | Limestone, P-70, olive gray; silty; laminated, locally cross-stratified, ripple-marked; porous; near the top almost pure limestone; indeterminate fossils | 4.2 |
| | Disconformity: distinct | |
| $Q_1$ | Siltstone, P-510, greenish gray; limy; top ripple-marked, locally showing slight relief | 0.8 |
| | Siltstone, P-509, brown, very slightly limy, laminated, locally ripple lamination; satinspar in veins | 9.8 |
| Q | Siltstone, P-506, greenish gray; limy; cross ripple lamination; small, indeterminate pelecypods, small gastropods, *Halicyne* common | 0.6 |
| | Siltstone, P-505, dark gray; limy; laminated; small indeterminate mollusks, ostracods | 2.2 |
| P | Siltstone, greenish gray; limy; middle part deformed by subaqueous slumping; ripple lamination | 6.0 |
| O | Siltstone, P-503, gray, limy, laminated | |

| | | |
|---|---|---|
| | and ripple-marked; irregular lenses of silty limestone; *Aviculopecten*, *Myalina*, *?Pseudomonotis* | 16.3 |
| N | Limestone, P-501, 502, green gray, very silty; bedding uneven; abundant terebratulids; *Myalina*, *Monotis*, *?Pseudomonotis* rare | 0.8 |
| | Limestone, P-500, green gray; terebratulids abundant | 0.2 |
| | Disconformity | |
| M | Siltstone, P-499, gray, limy; lenses of silty limestone near the top; Terebratulas common, "*Pugnoides*" rare | 1.2 |
| | Siltstone, P-498, green gray, limy; inclusions of siltstone up to 2 inches in diameter, terebratulids | 0.2 |
| L | Limestone, P-496, green gray, silty; small inclusions of siltstone on bedding; terebratulids common | 0.3 |
| | Siltstone, P-495, 497, green, very limy; terebratulids and "*Pugnax*" abundant | 0.2 |
| | Limestone, P-493, 494, gray, slightly silty; structureless; crinoid fragments locally abundant, terebratulids abundant, small gastropods common, *?Spirobis*, ?worm trails | 1.3 |
| | Limestone, P-492, green gray, very silty; interference ripple marks on top; ostracods | 0.6 |
| | Limestone, P-491, dark gray; silty; structureless; ostracods | 1.0 |
| | Limestone, P-490, green gray; silty; ostracods | 0.3 |
| | Limestone, P-486-489, gray; silty; flaggy, irregular; very fossiliferous at the top | 0.5 |
| | Disconformity: slight relief | |
| I | Siltstone, P-64, 485, 507, gray; shaly, fissile; irregular thin lenses of silty limestone; ripple marks; *Pleurophorus*, *Bakewellia*, *Myalina*; in the lowermost 7 feet *Tirolites spinosus*, *?Cordillerites*, *?Hungarites* | 41.6 |
| G | Limestone, P-484, greenish gray, silty; very abundant pelecypods | 0.5 |
| | Limestone, P-483, gray; dense; irregular shaly; crinoid fragments abundant, *Aviculopecten* and *Myalina* rare | 0.8 |
| | Limestone, P-482, olive gray; silty; irregular bedding; crinoid fragments abundant, indeterminate brachiopods | 2.0 |
| | Limestone, P-481, gray, silty; irregular shaly; brachiopods | 0.5 |
| | Limestone, P-480, gray, massive; brachiopods replaced by calcite | 2.0 |
| | Disconformity: very slight relief | |
| F | Siltstone, P-57, gray, calcareous; shaly, fissile; irregular lenses of silty limestone; *Monotis*, *?Pseudomonotis*, *Pleurophorus*, *Bakewellia* | 46.6 |
| C | Limestone, P-49-52, gray, locally silty; pronounced "torrential" cross-stratification; upper surface bevelled; stylolites; crinoid fragments abundant to common | 4.0 |
| | Disconformity: a slight relief | |
| B | Siltstone, brownish gray, limy (slope covered by talus) | 9.0 |
| A | Limestone, P-53, gray, crystalline; silty at the base; massive; crinoid fragments common, Terebratulas rare to common | 2.6 |
| | Limestone, P-54, gray, crystalline, dense; thick-bedded; rare, indeterminate fossils replaced by calcite | 3.6 |
| | Limestone, P-55, dark gray, silty; laminated | 2.2 |
| | Limestone, P-56, olive gray, very silty; laminated; limy siltstone inclusions in the lowest layer | 1.0 |
| | Unconformity: moderate relief | |
| | "Lower red member" of the Moenkopi group | |

*Section 6*

| | | |
|---|---|---|
| | Top of hill; recent erosion surface | |
| | Virgin formation: | |
| X | Limestone, P-551, white gray, silty; irregular siliceous thin layers; bedding shaly, eneven; small gastropods, probably Pleurotomariidae | 6.6 |
| | Disconformity: slight relief | |
| $V_2$ | Siltstone, P-550, gray, limy, shaly; satinspar in veins and on bedding planes | 1.6 |
| $V_1$ | Siltstone, P-549, brown, slightly limy; thin-bedded and laminated; alternates with green-gray limy siltstone; satinspar mainly in veins | 14.3 |
| V | Silstone, P-548, green gray; calcareous; uppermost 10 inches coprolitic | 8.2 |
| U | Limestone, P-547, gray, silty; laminated; alternates with limy siltstone laminae; ripple marks; *?Pseudomonotis*, *Aviculopecten* | 2.8 |
| T | Siltstone, P-546, gray, limy; locally laminated | 12.3 |
| S | Limestone, P-545, light gray, silty; laminated; uppermost 10 inches are white gray, with fossils replaced by calcite | 3.8 |
| | Limestone, P-544, gray; dense; massive | 2.0 |
| | Limestone, P-543, dolomitic, yellow gray; silty; laminated and ripple-marked | 0.2 |
| | Disconformity: very slight relief | |

| | | |
|---|---|---|
| $Q_1$ | Siltstone, P-542, light gray; limy; laminated; locally ripple-marked | 0.3 |
| | Siltstone, P-541, brown, limy; laminated and ripple-marked; alternating with green gray, limy siltstone laminae | 15.5 |
| Q | Siltstone, P-540, green gray, limy; laminated and ripple-marked; small gastropods | 2.2 |
| P | Siltstone, P-537-539, gray, limy; intricately folded; "shell and cast" structure, locally ripple-marked; deformation due to subaqueous slumping | 2.5 |
| O | Siltstone, P-536, gray, limy, micaceous; laminated and locally ripple-marked | 5.3 |
| | Siltstone, P-535, gray, limy, micaceous; thin- and thick-bedded; ripple marks common the the upper part | 11.3 |
| N | Limestone, gray, silty, laminated and ripple-marked; alternating with limy siltstone laminae; very poorly preserved mollusks | 1.0 |
| | Limestone, P-533, olive gray, silty; irregular thin-bedded and ripple-marked; poorly preserved pelecypods | 0.3 |
| | Disconformity: slight relief | |
| M | Siltstone, P-532, dark gray, limy; laminated; ripple marks on top; terebratulids and *Aviculopecten* rare to common | 1.0 |
| L | Limestone, P-530, 531, 534, gray; silty; irregularly laminated; *Myalina*, *Aviculopecten*, terebratulids, abundant | 0.6 |
| | Limestone, P-529, gray, crystalline; irregular inclusions of siltstone at the base; mud cracks up to 4 inches deep and up to 1 inch wide, at the top; crinoid fragments abundant, some pelecypods | 0.8 |
| | Disconformity: slight relief | |
| K | Siltstone, P-528, dark gray brown, limy; laminated; uppermost 4 inches gray green and with ripple marks | 2.3 |
| J | Limestone, P-527, gray; silty; poorly preserved pelecypods | 0.3 |
| I | Siltstone, P-525, gray, limy; laminated and thin-bedded; thin lenses of gray silty limestone; *Tirolites* in the lowermost 6 feet | 20.8 |
| G | Limestone, P-521-524, gray, crystalline; locally silty and coprolitic; massive; locally ripple-marked; stylolites; crinoid fragments abundant; very silty and very fossiliferous in the uppermost 7 inches, *Pleurophorus*, *Monotis*, *Pseudomonotis*, *Myalina*, *Bakewellia*, *Aviculopecten* | 4.5 |
| | Limestone, P-520, gray; ripple-marked and silty in the upper part; poorly preserved pelecypods, mainly ?*Pleurophorus* | 0.6 |
| | Limestone, P-519, green gray, very silty; irregular, thin bedding, ripple marks at the top; poorly preserved *Monotis*; ostracods | 0.8 |
| | Limestone, P-518, gray, crystalline; massive, ripple-marked near the top; *Pseudomonotis*, *Monotis*, most common near the top; small siltstone inclusions at the base | 0.6 |
| | Disconformity: slight relief | |
| F | Siltstone, P-514-517, gray; brown gray in the upper 6 feet, green gray uppermost 4 inches; limy throughout, with gray silty limestone thin, irregular lenses; laminated and ripple-marked; interference ripple marks at the top; *Monotis*, *Myalina*, ?*Pseudomonotis*, *Bakewellia*, ?*Pleurophorus* | 47.3 |
| C | Limestone, as unit "C" in section 1 and 3, with bevelled upper surface | |

*Section 7*

Top of hill; recent erosion surface

Virgin formation:

| | | |
|---|---|---|
| T | Siltstone, green gray, limy; exposed about | 6.0 |
| S | Limestone, gray and olive gray, silty; thin-bedded | 3.5 |
| | Limestone, P-158, gray, crystalline, massive | 2.5 |
| | Disconformity: not pronounced here | |
| $Q_1$ | Siltstone, brown gray, limy | 9.0 |
| | Siltstone, gray, limy | 13.5 |
| P | Siltstone, gray to green gray, limy; intricately folded due to subaqueous slumping | 2.5 |
| O | Silstone, gray and brownish gray, limy, laminated | 22.8 |
| N | Limestone, gray, silty, laminated | 1.0 |
| M | Siltstone, P-153-157, green gray; laminated; fossiliferous | 1.3 |
| | Disconformity: not apparent here | |
| L | Limestone, P-150-152, gray, massive; silty near the top; abundant crinoid fragments, pelecypods common | 1.6 |
| | Disconformity: slight relief | |
| K | Siltstone, gray, limy; laminated; uppermost 4 inches green gray | 2.0 |
| J | Limestone, P-149, gray; green-gray, limy siltstone laminae on bedding; poorly preserved fossils; this limestone lenses out southward | 0.3 |
| I | Siltstone, P-161-165, gray, limy; laminated and ripple-marked | 20.6 |
| G | Limestone, P-138-147, gray; crystalline, massive; silty and thin, irregularly bedded at the top, in the middle, and at the base; crinoid fragments abundant; other fossils indeterminate | 4.5 |

Disconformity: slight relief

F Siltstone, dark gray, limy; green gray at the top; slope covered

*Section 8*

Top of hill; recent erosion surface

Virgin formation:

X Limestone, white, porous; irregularly laminated; locally silty and siliceous.. 5.8

Disconformity

$V_1$ Siltstone, brown gray, slightly limy; gypsiferous; satinspar in veins..... 17.0

V Siltstone, P-176, green gray, limy..... 9.0

U Limestone, gray, crystalline; laminated and ripple-marked; with laminae of silty limestone; poorly preserved fossils..... 2.6

T Siltstone, greenish gray, limy, laminated..... 14.0

S Limestone, P-173-175, 177-178, gray; silty at the top; fossiliferous..... 1.7

Disconformity: very slight relief

$Q_1$ Siltstone, dark brown gray, slightly limy; with gray limestone lens near the top, and with 4 inches of gray, limy siltstone at the top..... 7.2

Q Siltstone, gray, limy; laminated..... 10.0

P Siltstone, gray to greenish gray, limy, micaceous on bedding; intricately folded due to subaqueous slumping... 2.3

O Siltstone, gray, limy; laminated; ripple marks common..... 17.7

N Limestone, P-171-172, greenish gray; silty on bedding; fossiliferous..... 0.3

M Siltstone, gray, limy; laminated..... 0.4

L Limestone, P-169-170, green gray, silty; fossiliferous..... 0.2

Siltstone, green gray, limy..... 0.2

Limestone, P-166-168, gray, dense; massive; locally porous; crinoid fragments abundant; brachiopods and pelecypods common..... 3.5

Disconformity: slight relief

I Siltstone, gray, limy; irregular laminae, ripple marks throughout, especially at the top; in the lowermost 6 feet poorly preserved cephalopods..... 21.0

G Limestone, like unit "G" in section 7; fossiliferous..... 4.6

Disconformity: slight relief

F Siltstone, dark gray, limy; with silty limestone nodules; worm trails..... 8.3

Limestone, P-192, gray, silty; fossiliferous; lenticular layer..... 0.1

Siltstone, gray, limy; with silty limestone thin lenses and small irregular concretions; poorly preserved pelecypods and small gastropods..... 31.3

C Limestone, P-193-196, gray, silty; fossiliferous; lower part covered by talus; exposed only..... 0.6

*Section 10*

Top of hill; recent erosion

Virgin formation:

D Limestone, P-257-260, gray, crystalline; stylolites; abundant crinoid fragments..... 3.8

C Limestone, P-253-256, gray, fine to coarse crystalline; poorly preserved brachiopods; the bottom irregular... 2.7

Disconformity along pronounced stylolites

A Limestone, P-252, gray, silty; poorly preserved fossils..... 0.4

Limestone, P-251, gray, crystalline; thick-bedded..... 1.5

Limestone, gray, silty; thick-bedded... 2.3

Limestone, P-248-250, gray, silty; almost pure limestone in the upper part; thin- and thick-bedded..... 5.2

Unconformity

"Lower red member" of the Moenkopi group

*Section 11*

"Middle red member"

Virgin formation:

Y Siltstone, P-297, siliceous, to silty chert, white; almost structureless; small mollusks, indeterminate..... 0.6

X Limestone, P-293–296, gray; dense, crystalline; silty in the middle of the layer; thin-bedded; irregular bedding near the bottom; fossils replaced by calcite; galena crystals disseminated; base irregular..... 5.0

Disconformity: slight relief

$V_2$ Limestone, P-292, light gray to white; laminated, ripple-marked, and locally cross-bedded; alternates with laminae of limy siltstone; inclusions of gypsum up to 5 mm. in diameter..... 3.6

Disconformity: slight relief

$V_1$ Siltstone, dark brown; locally gypsiferous..... 12.6

V Siltstone, P-290-291, gray, limy; alternates with green-gray, silty limestone 1–4 inches thick lenticular layers; ripple-marked; poorly preserved mollusks..... 11.6

U Limestone, P-289, gray, silty; massive; ripple marks at the top..... 0.6

| | | |
|---|---|---|
| $T_1$ | Siltstone, brown gray, gypsiferous; greenish in the uppermost 10 inches | 3.3 |
| | Gypsum, greenish gray, silty; thin, irregular bedding | 0.6 |
| | Siltstone, light greenish gray; gypsiferous, silty; nearly structureless | 2.5 |
| | Siltstone, gray, gypsiferous; irregular layers | 2.0 |
| T | Siltstone, P-288, gray, limy; conchoidal fracture | 1.6 |
| S | Limestone, P-287, gray, dense, massive; fossils replaced by calcite | 0.8 |
| | Limestone, P-287, gray, silty; laminated; locally cross-stratified; small limy concretions | 1.6 |
| | Disconformity: slight relief | |
| | Siltstone, P-286, greenish gray; laminated; locally cross-laminated; banded with gray, gypsiferous siltstone; satinspar in fractures | 2.8 |
| $Q_2$ | Siltstone, P-285, brown; gypsiferous; laminated; satinspar; gypsum laminae in uppermost 3 feet | 15.0 |
| P | Siltstone, P-284, gray, limy; laminated; ripple marks; locally deformed by subaqueous slumping | 5.0 |
| O | Siltstone, P-283, dark gray; limy; laminated; locally cross ripple-laminated | 16.6 |
| N | Limestone, P-278-282, gray; massive; very silty at the top; crinoid fragments, terebratulids, "*Pugnoides*" abundant; *Myalina*, *Aviculopecten* common to abundant | 1.8 |
| | Disconformity: slight relief | |
| $I_1$ | Siltstone, brown gray; laminated | 6.6 |
| I | Siltstone, P-277, dark brownish gray; limy, micaceous on bedding, laminated; *Tirolites spinosus*, "*Orthoceras*," in the lowest 6 feet; other mollusks very poorly preserved | 13.3 |
| G | Limestone, P-267-268, gray, crystalline, slightly silty; thin, irregular bedding; fossils replaced by calcite | 1.3 |
| | Limestone, P-269, gray, crystalline; "torrential" cross-bedding; greenish gray siltstone small inclusions | 1.6 |
| | Limestone, P-270-271, gray, crystalline; locally silty; massive; crinoid fragments abundant, ?worm trails | 1.8 |
| | Limestone, P-272-273, gray; silty, locally crystalline; thick-bedded; crinoid fragments common, brachiopods and pelecypods rare, poorly preserved; the thickness varies within a few yards | 2.9 |
| | Disconformity | |
| F | Siltstone, P-274, dark gray, slightly limy; laminated; the uppermost 8 inches are green gray, with brown gray layer 1 to 2 inches thick on top | 5.0 |
| | Siltstone, P-275, green gray, limy; micaceous on bedding; irregular small nodules of limy, hard siltstone up to 4 inches in diameter, and limy siltstone inclusions up to 1 inch in diameter; laminated and cross ripple-laminated | 1.6 |
| | Siltstone, dark gray, limy; micaceous on bedding; poorly preserved *Bakewellia*, *Pleurophorus*, *Myalina*, few *Aviculopecten* | 29.0 |
| C | Limestone, P-265, gray; silty; cross-ripple lamination in the upper part; crinoid fragments abundant, pelecypods common | 0.8 |
| | Limestone, P-264, gray, crystalline; crinoid fragments abundant | 0.5 |
| | Disconformity: here not apparent | |
| B | Siltstone, brownish gray; slope covered by talus | 9.3 |
| A | Limestone, P-261, gray; thin-bedded; brachiopods replaced by calcite | 0.9 |
| | Limestone, P-262, gray; "torrential" cross-stratification; porous in the middle of the layers; fossils indeterminate, replaced by calcite | 2.4 |
| | Limestone, P-263, gray, crystalline; only upper part exposed | 1.3 |
| | Contact with underlying strata covered by talus | |
| | Unconformity: here covered by talus | |
| | Alpha member of the Kaibab formation | |

*Section 12*

| | | |
|---|---|---|
| | "Middle red member" of the Moenkopi group | |
| | Virgin formation: | |
| Y | Siltstone, P-343, light gray; siliceous and limy; almost a silty chert; indeterminate mollusks | 0.6 |
| X | Siltstone, P-344, 479, white, limy; with indeterminate pelecypods and brachiopods | 1.8 |
| | Disconformity: moderate relief | |
| $V_3$ | Siltstone, P-342, white; limy, gypsiferous; alternates with lenticular layers of silty gypsum; the thickness of gypsum layers increases upward; siltstone fragments embedded in gypsum | 10.8 |
| | Disconformity: moderate relief | |
| $V_1$ | Siltstone, P-341, dark brown; slightly limy gypsiferous, up to | 8.3 |
| V | Siltstone, P-340, greenish gray; limy; satinspar in fractures | 18.3 |
| U | Limestone, P-338, 339, gray, dense; massive; stylolites; indeterminate fossils | 2.0 |

| | | |
|---|---|---|
| | Limestone, P-337, gray, silty; structureless | 1.2 |
| | (Unit "U" varies in thickness between 4 inches and 10 feet over short distances) | |
| $T_1$ | Siltstone, P-336, dark brown; slightly limy, gypsiferous | 3.5 |
| T | Siltstone, P-335, greenish gray; limy; laminated | 3.5 |
| S | Limestone, P-334, gray, crystalline, dense | 0.6 |
| | Limestone, P-333, gray, silty; laminated | 1.5 |
| | Disconformity: slight relief | |
| $Q_2$ | Siltstone, P-332, dark brown; gypsiferous throughout, especially near the top; gypsum layers up to 4 inches thick | 12.0 |
| P | Siltstone, P-331, greenish gray, alternating with limy siltstone; all ripple-marked; deformed by slumping | 5.8 |
| O | Siltstone, P-330, gray, limy, micaceous on bedding; with limy, hard siltstone thin layers, and nodules; thin-bedded and laminated | 20.6 |
| N | Limestone, P-329, 478, greenish gray; silty; ripple-marked; mud cracks in the middle of the layer; *Myalina*, *Bakewellia*, crinoid fragments, worm trails near the top | 1.5 |
| M | Siltstone, P-328, dark gray, limy, laminated | 1.6 |
| L | Limestone, P-326, 327, 477, gray crystalline; massive; silty near the top; crinoid fragments abundant, brachiopods abundant, *Aviculopecten* rare | 1.4 |
| | Disconformity | |
| I | Siltstone, P-302, 325, 476, gray and dark gray, limy; poorly preserved pelecypods abundant; cephalopods rare, *Tirolites spinosus* in the lowermost 6 feet | 21.8 |
| G | Limestone, P-323, 324, 475, gray; massive, irregular bedding; individual layers silty near the bottom, almost pure limestone near the top of the layers; crinoid fragments abundant; a few brachiopods; *Aviculopecten*, *Myalina*, *Bakewellia* common; gastropods rare; vermes incertae sedis; lower boundary of the unit covered by talus; exposed only | 5.5 |
| | Disconformity: here covered by talus | |
| F | Siltstone, P-321, 322, 298–302, 474, gray, limy, micaceous on bedding; irregular laminae; alternating with hard limy siltstone lenticular layers, and concretions; *Bakewellia*, small *Myalina* common in the lower part | 45.0 |
| D | Limestone, P-320, 473, gray, crystalline; silty near the top; crinoid fragments common; terebratulids and pelecypods rare to common | 3.0 |
| C | Limestone, P-319, 472, gray, crystalline; siltstone inclusions up to 1 inch in diameter near the base; stylolites; cross-stratification, upper surface bevelled; crinoid fragments abundant, other fossils indeterminate; the thickness varies from 1 foot 2 inches to | 3.1 |
| | Disconformity: pronounced relief | |
| B | Siltstone, P-317, 318, brown, limy; the uppermost 4 inches are gray and not calcareous; bedding irregular; top ripple-marked; up to | 2.6 |
| A | Limestone, P-316, 471, light gray, dense | 0.6 |
| | Limestone, P-470, gray, dense; oölitic; stylolites | 0.7 |
| | Limestone, P-469, light gray, silty; thin-bedded; poorly preserved pelecypods | 0.6 |
| | Limestone, P-315, gray, dense; lower surface uneven; 1 foot to | 1.3 |
| | Limestone, P-314, 468, gray; dense; ?biohermal | 1.6 |
| | Limestone, P-313, 467, gray; cross-stratified; lenses of silty limestone mark cross-bedding; mud cracks on top | 0.8 |
| | Limestone, P-312, 468, gray, dense; lenticular; fossils calcified; up to | 0.6 |
| | Limestone, P-465, gray, silty; partly eroded; lenticular; up to | 0.1 |
| | Limestone, P-311, 464, gray; "torrential" cross-bedding; thickness 2 inches to | 0.3 |
| | Limestone, P-310, gray; lenticular; brachiopods poorly preserved; up to | 0.2 |
| | Limestone, P-309, 463, gray, dense, massive; silty near the bottom | 1.2 |
| | Limestone, P-308, 462, gray, silty; laminated | 0.6 |
| | Limestone, P-461, gray, dense; lenticular; 1 inch to | 0.2 |
| | All the limestones of this unit ("A") overlie each other disconformably | |
| | Unconformity: considerable relief | |
| | Kaibab formation; lower part of the gypsiferous alpha member | |

*Section 13*

| | | |
|---|---|---|
| | Top of hill; recent erosion surface | |
| | Virgin formation: | |
| N | Limestone, P-414, gray, crystalline, porous; thick-bedded | 5.6 |
| | Disconformity: slight relief | |
| L | Limestone, P-413, gray, crystalline; | |

| | | |
|---|---|---|
| | structureless; small indeterminate fossils | 0.6 |
| | Limestone, yellow gray, silty; thin- and thick-bedded | 4.6 |
| | Limestone, P-412, gray, silty, crystalline | 0.3 |
| | Disconformity: here covered by talus | |
| I | Siltstone, P-411, gray, limy; thin-bedded and laminated; covered by talus; poorly preserved mollusks; "*Orthoceras*" in the lower 6 feet | 27.5 |
| G | Limestone, P-410, gray, dense; lenticular, irregular, thin layers; crinoid fragments; pelecypods, small gastropods; vermes | 6.3 |
| | Disconformity: here concealed | |
| F | Siltstone, P-409, gray, limy; poorly preserved pelecypods; slope covered by talus | 57.3 |
| D | Limestone, P-408, gray, dense; crinoid fragments; indeterminate pelecypods and brachiopods | 0.7 |
| C | Limestone, P-407, greenish gray, silty; thin, irregular bedding; with dense limestone thin layers; crinoid fragments, indeterminate pelecypods and brachiopods, replaced by calcite; exposed about | 1.6 |
| | The rest of the section covered by talus | |

*Section 14*

| | | |
|---|---|---|
| | Top of hill; recent erosion surface | |
| | Virgin formation | |
| X | Limestone, P-360, gray, crystalline; thin-bedded; crinoid fragments abundant | 4.0 |
| | Limestone, P-359, gray, silty; irregular bedding | 4.0 |
| | Contact covered; probably disconformity | |
| W | Siltstone, brown, gypsiferous; slope covered by talus | 44.6 |
| P | Siltstone, P-358, gray, limy; thin-bedded, ripple marks; deformed by slumping; raindrop imprints, trails of indeterminate animals | 1.6 |
| O | Siltstone, gray, limy; laminated | 1.6 |
| N | Limestone, P-357, gray crystalline; near the top silty and with green gray siltstone small inclusions | 2.4 |
| | Disconformity: no apparent relief | |
| I | Siltstone, P-355, 356, dark gray; limy; laminated; pelecypods; cephalopods in the lowermost 6 feet | 41.3 |
| G | Limestone, P-353, 354, greenish gray; massive; silty, especially near the top; crinoid fragments abundant, poorly preserved pelecypods abundant on the upper surface | 2.5 |
| | Disconformity: no apparent relief | |
| F | Siltstone, P-351, 352, gray, limy; irregular laminae; numerous hard limy siltstone thin lenses and concretions; *Bakewellia*, *Myalina* | 50.0 |
| D | Limestone, P-347–350, gray, crystalline; crinoid fragments abundant in the upper part; poorly preserved mollusks replaced by calcite, in the middle part | 4.6 |
| C | Limestone, P-345, 346, gray, crystalline; structureless; hard limestone concretions up to 2 feet in diameter in the uppermost part; crinoid fragments abundant, brachiopods rare | 5.8 |
| | Lower part of this limestone covered by talus. | |

*Section 15*

| | | |
|---|---|---|
| | Top of hill; recent erosion surface | |
| | Virgin formation: | |
| X | Limestone, P-392, gray, crystalline; thick-bedded; up to | 5.0 |
| | Limestone, P-391, gray, dense, crystalline; thick, irregular beds; indeterminate fossils replaced by calcite; up to | 10.8 |
| | Disconformity: no apparent relief | |
| W | Siltstone, brown, gypsiferous; slope covered by thick mantle of talus; the excessive thickness may be due to the repetition by thrust faulting which is likely to be present here | 78.0 |
| $P_1$ | Limestone, P-389, 390, greenish gray, very silty; ripple marks; crinoid fragments rare, pelecypods, *Aviculopecten* common | 2.0 |
| O | Siltstone, gray, limy; slope covered by talus | 5.6 |
| N | Limestone, P-386-388, greenish gray; crystalline; silty in the upper part; crinoid fragments abundant in crystalline limestone | 1.0 |
| | Disconformity: very slight relief | |
| I | Siltstone, P-384-385, gray, limy; micaceous on bedding; irregular ripple lamination; reddish brown and greenish gray near the top; ostracods | 41.6 |
| H | Limestone, P-383, olive gray, silty; fossils replaced by calcite | 0.8 |
| | Probably siltstone; slope covered by talus | 0.8 |
| G | Limestone, P-380-382, gray; crystalline; silty near the top; massive, ripple-marked in the upper part; crinoid fragments abundant in the crystalline lower part, common in the silty, upper part; pelecypods common | 4.2 |
| | Disconformity: no apparent relief | |
| F | Siltstone, P-378-379, gray, limy; lami- | |

creases upward within the unit, as in units "F" and "V". In these it forms layers of silty limestone, 1–2 inches thick, interbedded with moderately limy siltstone.

The lithology and faunas of the gray siltstones indicate a marine environment of deposition. Their composition and structure suggest that sediments were laid down in relatively shallow, quiet waters or on extensive tidal plains which were occasionally exposed to subaerial weathering. Intermittent subsidence of the sea floor probably initiated new periods of deposition which continued until the sedimentary basin was again filled, causing withdrawal of the seas.

During regression, the uppermost strata of the gray siltstone units apparently were exposed either to atmospheric conditions or to the action of fresh or slightly brackish water. Such changes in environment removed the $CaCO_3$ from the uppermost strata and leached them. A thin reddish stratum at the top of a leached zone in one place suggests either a change in the source of the clastic material, a different environment of deposition, or weathering.

Uniform size of detrital particles, and presence in the siltstones of only very stable minerals like quartz and muscovite, suggest transportation or reworking by the sea which eliminated less stable minerals. This implies either (1) a distant source area for the components of the sediments, and extremely slow transportation, such as would be possible only with a very broad coastal plain; or (2) their derivation from already well-sorted sediments; or (3) a long time of reworking before final deposition.

*Marine brown siltstones.*—The group of siltstones referred to as "marine brown siltstones" is represented by units "$I_1$" and "$Q_1$". Siltstone of unit "$Q_1$", which occurs in the upper part of the northern sections (1–8), overlies unit "Q", a typical marine gray siltstone, while unit "$I_1$", present only in the middle of section 11, overlies "I", also a normal marine gray siltstone.

Contacts of the marine brown siltstones with the underlying units of gray siltstone are clearly marked, but the relations are conformable. The two types of siltstone differ mainly in color. The marine, brown siltstones are overlain disconformably by limestones, except in section 1, where the unit "$Q_1$" apparently is overlain conformably by the very limy siltstone, "R".

These siltstones are brown, brownish gray, or dark brownish gray, with a few streaks of greenish gray formed by silt. The siltstones are mainly silt-sized particles of quartz, minute flakes of muscovite, and a matrix of clay. Very small grains of magnetite form a thin film on uneven bedding planes. Laminae of silt in unit "$Q_1$" of section 6 are distinct greenish gray. Their lime content is abnormally high for these brown siltstones.

The siltstone of unit "$Q_1$" in the uppermost 1 foot 4 inches is light gray. Thin layers are interbedded with greenish-gray claystone and contain, in the middle, limy yellow laminae of claystone. This unit is calcareous and grades laterally, south of section 8, into gypsiferous siltstones of lagoonal origin (Fig. 4).

No fossils have been found in these siltstones. The ripple marks and mud cracks in the brown siltstones suggest formation in very shallow marine waters in a basin always filled or nearly filled with sediments.

*Calcareous, gypsiferous siltstones.*—A group of siltstones transitional between marine and continental strata is represented by units "$Q_2$", "$T_1$", "$V_1$", and "$V_2$". This group occurs in the upper part of the stratigraphic columns, north of section 14.

The calcareous, gypsiferous siltstones grade laterally into marine gray siltstones toward the northwest, and into lagoonal sediments toward the southeast. The highest siltstone, "$V_1$", reaches farthest north. Each unit is set off by sharp lithologic boundaries both above and below. The upper boundary is everywhere disconformable.

The calcareous, gypsiferous siltstones range from dark brown, through brown, to brownish gray. Some of the most strongly gypsiferous beds, however, are distinctly gray or greenish gray, as siltstone P-286 and unit "$T_1$" in section 11. Thin layers of greenish-gray siltstone (up to 1 cm thick) alternate in most places with brown siltstone, especially in the upper parts of the units.

The siltstones are mainly quartz grains of

silt size or smaller, mostly well sorted and graded. A few laminae of sandy siltstone occur in the upper part of unit "$V_1$" in section 6. Very small magnetite crystals are disseminated throughout and locally are concentrated to form a thin film on bedding planes.

The cement consists largely of gypsum and minor calcium carbonate. Gypsum also occurs in irregular layers that are progressively more abundant and thicker toward the top of each calcareous, gypsiferous siltstone unit. Individual layers of gypsum range up to 4 inches thick. The upper part in most of the units is composed of laminae of gypsum. Veins of satinspar are found in fractures.

Layers of gypsum are associated in many places with gray siltstones of the calcareous, gypsiferous siltstone group. Where the relative abundance of gypsum cement is great, the particles of silt are suspended in crystals of gypsum, forming green-gray layers of "gypstone" (Shrock, 1948, p. 65, used the name "gyprock") that are more resistant to weathering than the surrounding rocks.

Above "$V_1$" in section 6 is a layer of gray, silty and limy, shaly claystone and siltstone 1 foot 8 inches thick, unit "$V_2$". In the middle of this unit occur three yellow-brown or brownish-gray layers, each about 1 inch thick. On top of the unit are ripple marks 4 inches in amplitude and 2 feet long.

No traces of life have been noted in the calcareous, gypsiferous siltstones. The presence of calcareous and gypseous cement, and the intercalation of gypsiferous layers with dominantly calcareous layers, especially in the upper parts of the units, indicate deposition under conditions unfavorable to life. There seems to have been wide fluctuation in the relative amount and concentration of carbonate and sulfate ions, or in the conditions that resulted in the precipitation of one or the other.

*Noncalcareous, gypsiferous siltstone.*—The noncalcareous, gypsiferous siltstone of unit "W" was not examined because of poor exposure. This rock is brownish gray and reddish brown. It has a fine, uniform grain size and contains thin-bedded and laminated layers of gypsum.

Two types of gypsum occur in the noncalcareous, gypsiferous siltstone unit. One is greenish gray, has a ribbonlike lamination, and contains silty particles in varying concentrations; the other consists of white, crystalline gypsum, thin-bedded and lenticular in most places.

A very slight calcium-carbonate content has been noted. From the scant data available, it is believed to have formed under lagoonal conditions.

*Coprolitic siltstone.*—Conformably overlying unit "$Q_1$" in section 1 is unit "R", designated as "coprolitic siltstone" 12 feet thick. It is not known from any other section. It is disconformable with overlying limestone.

The coprolitic siltstone is light yellowish-brown in its lower part and grades upward into light yellowish-gray.

The lowest 2–3 feet of the rock is mainly silt-sized, angular and subangular quartz and fine-grained muscovite. The component grains are finer toward the top of the unit. In the uppermost part of unit "R" the detrital particles are clay size, but subrounded grains of white quartz, ranging up to 1 mm in diameter, are scattered throughout the fine matrix.

The very fine material in the uppermost 2 feet of unit "R" is aggregated into loosely cemented pellets, irregular in size and shape, but mostly spherical or ovoid. They are composed of a brownish clay and dissolve in hydrochloric acid, coloring it brown to dark-brown.

The lowest part of unit "R" is uniformly soft, thin-bedded, and laminated. The middle part consists of alternating soft and hard, thin-bedded and laminated layers. Laminae, 1–5 mm thick in the soft layers, are arranged in groups up to 2 inches thick. These alternate with harder layers of about the same thickness. The harder layers contain well-developed ripple marks. In the uppermost 2 feet of the unit, bedding is hardly visible.

Layers of iron-coated grains mark the bedding of the coprolitic siltstone, especially in the lower part. Some dark-brown spots occur throughout. Under the microscope, these spots appear to be formed from groups of minute quartz grains coated with hematite.

The coprolitic siltstone is porous and not well cemented. Porosity is progressively greater to-

ward the top. Field and laboratory tests show a low calcium-carbonate content.

The only fossils known are impressions of indeterminate small pelecypods in the lowest 3 feet and some very poorly preserved, small gastropods in the uppermost 2 feet.

The origin of the pellets that form the uppermost 2 feet of the coprolitic siltstone unit is debatable. They may be a faecal product of bottom-dwelling macro-organisms. Most have a simple ovate shape, but some resemble faecal pellets of Littorinidae illustrated by Moore (1931, Pl. 33).

Recent studies of sediments of the sea bottom (Dapples, 1942) show a wide distribution of coprolitic material at various depths. Tidal flats are one of the best environments for bottom dwellers that may greatly influence the accumulating sediments. Studies of recent tidal-flat deposits along the North Sea in Germany (Hantzschel, 1939) have shown that ellipsoidal excrements of polychaete worms and certain pelecypods living in the upper few cm of the deposits, and of gastropods *Littorina* and *Hydrobia* that feed on the surface of the deposit, may form a major part of the sediment.

Such material reworked on the sea floor by bottom-dwelling organisms may reach great thickness; in the Virgin formation it amounts to over 2 feet. Dapples has suggested that such organic "reworking" of sediments probably would destroy all traces of bedding.

The characteristics of the uppermost 2 feet of unit "R", and the similarity of the pellets to those of known faecal origin suggest that these uppermost strata should be interpreted as coprolitic. Coprolites have been observed locally also in the siltstones of unit "V".

*Color of siltstones.*—The color of the sediment components may solve the problem of the origin of the source material and of the environmental conditions during sedimentation, lithification, and diagenesis.

RED BEDS:—The origin of red beds has been given much attention by many writers, including Branson (1915), Dorsey (1926), and Krynine (1949).

The siltstones of the Virgin formation are mainly gray or "red." A true red is extremely rare in the formation and, when present, is of a limited, strictly local character. The term "red" as applied in the literature to "red beds" of the Moenkopi "formation" has been used for predominantly brown siltstones.

The mineral components of the sediments suggest the same source of the clastic material for both gray and brown siltstones. The silt particles imply a distant source area and slow transportation over a very broad coastal plain, or a long time of reworking. Nothing can be deduced from the sediments as to the source area itself.

Coastal plains over which the sediments may have been transported have not been recognized. An exception may be the alpha member of the Kaibab which could have contributed to the gypsiferous deposits of the Virgin formation.

Deposition took place in lagoonal, brackish-water, and marine environments, with lateral change of facies from continental (lagoonal) to marine. The brown siltstones may have been formed: (1) from detritus of existing red beds, reworked and sorted during transportation and deposited under the climatic conditions which permitted the preservation of red pigment; or (2) from nonred detrital rocks, the components of which acquired red pigment from the oxidation processes affecting ferruginous minerals during long transportation under relatively humid and warm climatic conditions and were deposited in an environment that preserved the red color; or (3) from nonred detrital rocks, the red color resulting from the oxidation of ferrous into ferric oxide in the depositional basin in the absence of reducing agents.

Under a normal marine, open-circulation environment the oxidation-reduction potential, Eh, has small positive value (0.2–0.4), and sea water represents mildly oxidizing conditions throughout. Chemical end members, stable in the oxidizing environment, are not subject to severe chemical change when buried in such an environment (Krumbein and Garrels, 1952, p. 27).

The precipitation of the red iron-oxide pigment from solution is improbable in the case of the "red" siltstones of the Virgin formation. The pigment occurs as a coating on silt grains, and not as a matrix or as concretions, as would be expected in the marine oxidates precipitated largely as gels.

The "red" color of the gypsiferous siltstones of the Virgin formation (unit "W", and its tongues "$Q_2$", "$T_1$", and "$V_1$") may be explained as follows:

The ferric oxide-coated grains of silt were blown by wind or transported by water during occasional cloud bursts into near-shore lagoons. The high salinity of these lagoons inhibited organic life, resulting in conditions which prevented or limited the reduction of the ferric oxide pigment.

Under a restricted arid environment high temperatures reduced the oxygen content and may have decreased the Eh value. The primary gypsum content in the matrix of some of the brown siltstones indicates that the prevailing water temperature during deposition was about 30°C.

The presence of gypsum both as cement in the "red" siltstones and as layers of almost pure material interbedded with siltstones, and absence of any traces of carbonaceous matter which could have caused reduction of iron-bearing minerals suggest subsequent deposition of primary red sediments in the zone of oxidation of shallow, lagoonal waters.

GRAY SILTSTONES: The gray siltstones range from bluish, through dark gray, to greenish gray or even green. Considering these colors there are following possibilities:

(1) Primary reddish sediments may have been reduced in the basin of deposition. The reduction may occur in the presence of organic matter decaying under anaerobic conditions and change the hydrous ferric oxide into sulfides or carbonates (Ruedemann, 1925, p. 85). Depending on the degree of reduction the color ranges from blue to green. According to Pettijohn (1949, p. 173) abundant carbon in the strata will inhibit oxidation of the iron and will reduce the higher oxides to the lower. In the absence of organic matter the sediment cannot change its red color by the reduction of ferric oxide into ferrous oxide.

Reducing conditions may also occur where the currents carrying oxygen-bearing surface water do not reach the bottom, or where the surface waters have been deprived of their oxygen by biological activity (Rankama and Sahama, 1950, p. 214).

(2) Primary nonred sediments may be deposited in the presence of organic matter which inhibits or limits the oxidation. A low degree of oxidation will give colors ranging from blue to green (ferrous oxide). In the absence of carbon or other reducing agents the sediments may retain their primary colors which may range from white to black.

### *Limestones*

*General.*—The limestones in the Virgin formation may be divided into: (1) silty limestones, (2) crinoidal limestone, (3) oölitic limestone, (4) chemically precipitated limestone, and (5) siliceous limestone. There are no wholly clastic, or any pure, chemically precipitated limestone in the formation. Considerable clastic material may be found in the lower part of the layer, and almost pure, probably chemically precipitated limestone near the top of the same layer. There is also a considerable lateral lithologic change, and the same layer may show marked lateral facies variation.

*Silty limestone.*—Most of the limestones may be classified as silty limestone, usually gray, ranging from slightly dark, through green, to olive-green, bluish, and light-green hues. Locally yellow or brownish-yellow colors are present, especially in the layers in the oxidizing zone. They contain essentially no carbonaceous matter. The organic material of decaying animals may have limited or prevented the oxidation of ferrous oxides or may have reduced the ferric oxides to ferrous oxides.

The insoluble residue in the limestones ranges from 1.1 to 50.0 per cent with the average content ranging from 15 to 25 per cent. Usually, it is higher in the lower parts of the limestones and diminishes toward the upper part of a single unit, where it tends to increase again forming a transition into the overlying siltstone. There are, however, units in which the insoluble residue content progressively increases toward the top.

The most common insoluble components of the silty limestones are, in order of decreasing abundance: angular and subangular to subrounded grains of quartz; locally, irregular, small aggregates of opal; and iron oxides, present usually as irregularly shaped, powdery aggregates and as a very fine coating on quartz grains. Hornblende (and possibly hypersthene),

galena, flakes of muscovite, and some feldspar are rare. They are disseminated throughout the rock although locally they may be concentrated in thin layers. A few irregular laminae of clay minerals cemented by opal are embedded in limestone.

The silt in the lowermost parts of limestone units may be concentrated into thin laminae of limy siltstone. The limestones that contain less than 10 per cent silty material have a fine crystalline texture. Those that are finely crystalline are dense and break with a conchoidal fracture.

The boundary between limestones and the underlying siltstones is always distinct. The upper boundary, between the limestones and the overlying siltstones, is not so prominent and is transitional. The silt content increases up to 50 per cent in the uppermost transitional part of the units.

The limestone of unit "G" locally is coprolitic. Marine fossils were observed in the silty limestone units throughout the formation. Most of the fossils are very poorly preserved, and many are replaced by calcite.

*Crinoidal limestone.*—This limestone is represented by unit "D" in sections 1, 10, and 12 to 17 (Fig. 4). The limestone ranges from almost white in the most northern locality, section 1, to light-gray in the southeastern sections. The color depends on the amount of insoluble residue. The nearly white limestone of section 1 contains less than 1 per cent, while the residue content in the darker (light-gray) limestones ranges from 3 to about 32 per cent.

The main components of these limestones are broken stems and plates of crinoids, entirely recrystallized. They are well sorted and of a uniform coarse size. A few fragments of thin-shelled terebratulids and aviculopectinid pelecypods are locally present. Like the insoluble residues they increase from the northwest toward the southeast, while the relative abundance of crinoid fragments diminishes in the same direction.

The cement of the crinoidal limestone is calcareous. A few small, irregular cavities have the walls covered by a thin film of iron oxides.

The limestones are massive and do not show bedding, except for a weak indication of cross-stratification in section 15.

The crinoidal limestones of unit "D" were deposited in relatively shallow and clear water, as evidenced by a low amount of silt in the most northern section (1), where the crinoidal content is highest. Apparently the turbidity of the water increased farther south where the limestones of unit "D" contain more silty material suggesting shallower and more turbulent conditions and the proximity of a shore line.

*Oölitic limestone.*—Irregular, thin, oölitic layers of limestone were observed in the upper part of unit "X", in section 16. The limestone is yellowish gray, massive, and very finely crystalline. Large crystals of calcite are disseminated throughout.

The oöids range from oölitic to pisolitic dimensions and show a varied degree of sphericity. Nuclei of the oöids consist of one or more minute crystals of calcite or dolomite. No nuclei of other composition were found in thin sections or on polished surfaces. Concentric growth laminae of most oöids consist of alternating deposits of calcite and dolomite. Many, however, are entirely calcite or dolomite.

Locally, several oöids form small concretions, most of which are spherical, but which may be irregular in shape. The space between the oöids within the concretions is filled with large crystals of calcite. The oöid concretions serve as centers of crystallization and show further concentric aggregation.

The space between adjacent concretions and between concretions and the separate oöids is also filled by large crystals of calcite. The walls of a few cavities are covered by crystals of calcite or dolomite. We do not know what concentrated single oöids into concretions. Neither the oöids nor the concretions show any sign of abrasion or sorting, and oöids of different sizes occur together.

Oölites supposedly form from the precipitation of calcite about nuclei in strongly agitated, shallow waters (Eardley, 1938, p. 1386). They may form also in shallow waters by rolling and spinning movement of the particles (Kuenen, 1950b, p. 220). Eardley (1938, p. 1359), studying the modern sediments of Great Salt Lake, Utah, observed that the most favorable sites for oölite development are shore lines which, facing the open lake, receive the

action of unimpeded waves. He also states that "the more vigorous the wave activity the larger and more typically developed the oölites and ordinarily cleaner the oölitic sand" (p. 1371). Twenhofel (1939, p. 630) says that oölites and pisolites are known also from strata that show little or no evidence of wave or current action.

In the Virgin formation the amount of agitation of water during the formation of oölitic layers is unknown.

*Chemically precipitated limestone.* — Pure, chemically precipitated limestones are present only locally. The limestone layers may contain considerable clastic material in the lower part and may show characteristics of a chemical precipitate in the upper part of the layer.

Several layers, especially within units "A", "C", "S", and "X", which probably have been chemically precipitated, locally have finely to coarsely crystalline grains. Most finely crystalline limestones are flaggy or massive and structureless. The layers are lenticular, and some of them grade laterally into silty limestones.

A few of the chemically precipitated limestones are dolomitic and sideritic, as the basal part of the limestone of unit "S", in section 6. This yellowish-gray limestone occurs in lenticular layers, 1 to 2 inches thick, that alternate with gray, dense, massive limestone. Thin bedding and even lamination is visible, however, on weathered edges. The rock is dense and breaks with a conchoidal fracture. Only a negligible amount of insoluble residue is present. Dolomitic limestone is represented by 8- to 12-inch layers in unit "S", in section 2 and 3.

*Siliceous limestone.*—The uppermost limestone, unit "X", is finely crystalline composed of minute calcite crystals of uniform size. Locally, it is distinctly siliceous.

The insoluble residue, mainly silica, ranges from 1.6 per cent in relatively pure, crystalline limestone to about 30 per cent in distinctly siliceous limestone. The lateral variation of silica is more pronounced than the vertical variation in unit "X".

Silica is present in the siliceous limestones mostly as small euhedra of authigenic quartz and as small spherulites of authigenic chalcedony which is disseminated and also concentrated in small irregular aggregates. Other main components are detrital quartz, feldspars partly altered to clay minerals, and muscovite. There also are thin layers of clay cemented by opal.

The siliceous limestone is massive and structureless, but shows lamination and thin bedding on weathered surface. It is light gray to yellowish gray. The less siliceous layers, composed of coarser crystals of calcite, are light gray or gray.

Small gastropods, probably Pleurotomaridae, are present locally but are very poorly preserved.

### *Cherts*

Chert was observed in limestone mainly in unit "S" in section 2; in unit "Y", in sections 11 and 12; and only locally in unit "X". It occurs in unit "S" as irregular, thin layers or lenses and as disc-shaped concretions from half an inch to more than 2 feet in diameter, and up to 1 inch in thickness. The cherts are concordant with the bedding or cross-stratification and are also distributed at random within the massive beds.

Most of the centers of chert concretions are dense, but many show a spongelike structure and are quartzitic. A thin peripheral zone of the concretions is porous in all specimens, with the intergranular spaces filled by calcite, dolomite, or hematite. The walls of some cavities (intergranular spaces) are covered by minute crystals of hematite. The boundary between the concretions and the surrounding rock is well marked by the darker color of the peripheral zone.

A thin section of a cherty concretion from the limestone of unit "S", section 2, revealed a matrix of chalcedony surrounding (1) abundant carbonate in rounded and ellipsoidal grains, pellets, and crystals, some stained black, probably by organic matter; (2) scattered detrital grains of quartz, feldspar, and a few of muscovite; (3) large opaque spots, satiny white in reflected light, that appear to be leucoxene. There is no indication as to what the original titanium mineral was that has altered to leucoxene, or whether the leucoxene

was deposited as such; (4) large patches of opal, with cracks filled with secondary chalcedony that has crystallized from the opal; and (5) iron-stained patches of carbonate, possibly from the weathering of finely disseminated pyrite?. These probably are coprolites.

Other concretions may have formed from colloidal silica of sea water, which was attracted by clastic quartz grains or other centers of crystallization or concretion. The intergranular spaces may have been filled at the same time with carbonates and with iron oxides. These cherty concretions may be compared to quartzitic chert concretions described by McKee (1938, p. 88) as type 3, from the beta member of the Kaibab.

No fossils were observed in or near concretions. Some of the fossils in the limestone of unit "S" are replaced by chert, but they are not connected with existing cherty concretions.

### *Gypsum*

Gypsum, an important component of the siltstones of the upper part of the Virgin formation, is present in units "$Q_2$", "$T_1$", "$V_1$", "$V_3$", and "W". These units form layers 6 to 50 feet thick, with the thickness increasing from northwest to southeast.

The gypsum occurs as: (1) aphanitic gypsum in the matrix of siltstones, occurring with a small amount of calcium carbonate; (2) free crystals of gypsum embedded in the matrix; (3) satinspar in veins and in spaces between the laminae of the siltstone; and (4) ribbonlike layers.

The amount of silt suspended in the gypsum averages 20 per cent. The dark gypsum contains up to 50 per cent silt, but the light-gray or white gypsum may have not more than 12 per cent. The evaporite portion of the rock is predominantly gypsum, but a small amount of calcium carbonate is present in all specimens. The calcium carbonate in the matrix of the brown siltstones decreases from north to south.

There are two possible sources for the gypsum:

(1) It may have originated through precipitation from sea water that had concentrated it by evaporation in lagoons. Water could have broken through a barrier into the lagoons during storms, or there might have been a shallow connection between the lagoons and the sea. The lagoons could have been replenished periodically or constantly with sea water.

(2) It may have been carried in solution or blown by the wind, from areas where the alpha member of the Kaibab was being eroded, into depositional basins which were also occasionally receiving sea water.

The absence of deformation in the gypsiferous strata indicates that gypsum was directly precipitated and is not a product of hydration of anhydrite. Only a few ribbonlike gypsum layers in unit "W" show slight deformation. Syngenetic internal structures, such as ripple marks and ripple laminae in the gypsiferous siltstones, suggest a lagoonal, saline, shallow-water environment.

The absence of primary structures in parts of the strongly gypsiferous siltstones suggests uninterrupted deposition locally below the wave action. The greater density of lagoonal water caused by evaporation may have modified the waves, so their action was shallower than in the basins containing normal sea water. Small lagoons would also limit the amplitude of waves and diminish their influence on the sediments.

The conditions postulated for formation of the gypsiferous siltstones under restricted arid environment are found in modern lagoons. The classic example is the Gulf of Karabugaz, on the eastern side of the Caspian Sea, surrounded by desert on three sides. The average depth of the gulf is not more than 50 feet. It is separated from the Caspian Sea by narrow sand spits (Grabau, 1920, p. 132). A shallow, narrow (100–500 meters) strait, 5 km long, is the only connection with the Caspian Sea. The current passing through this strait always flows from the Caspian Sea toward the gulf. The current has a minimum velocity 24.5 meters per minute in November and increases to over 44 meters per minute during the summer, when the water level in the gulf falls because of increased evaporation. This stream carries into the gulf a daily load estimated at 350,000 tons of salt.

This gulf represents the extreme case for the formation of gypsum in considerable quantity.

The barrier does not permit the outflow of dense water from the gulf, while hydrostatic equilibrium causes the inflow of the "normal" Caspian Sea water into the gulf. The density of the surface water in quiet basins increases with evaporation, and the heavier water settles. Gypsum will precipitate from solution when the salinity increases to 3.5 times the normal concentration of sea water, at or near 30°C. The precipitation will continue until the salinity reaches approximately 4.8 times the normal salinity of sea water. Beyond this point the calcium sulfate will be precipitated as anhydrite. Hydrogen-ion concentration (pH) required for precipitation under restricted arid environment is 8 to 9. The pH value of the Caspian Sea ranges between 7.6 and 8.6 (von Raupach, 1952, p. 92). The pH increases with increasing salinity.

When gypsum was precipitated in the upper part of the Virgin formation, fine particles of clay or silt were being transported by wind or water into the depositional basin and may have formed nuclei for the precipitation of gypsum. The primary coating on silt grains is responsible for the "red" gypsiferous siltstones. The cement is hydrous calcium sulfate and calcium carbonate.

The association of gypsum with calcium carbonate has been noted by McKee (1938, p. 123) in Toroweap alpha, facies 1, from Hilltop, near Havasu Canyon, Arizona. There the gypsum is not replacing the limestone but fills fractures and cavities in older limestone.

In the gypsiferous siltstones of the Virgin formation, gypsum is the dominant mineral of the matrix. The gypsum did not replace the limestone, and it seems certain that gypsum and calcite were precipitated contemporaneously.

The association of calcium carbonate and gypsum has been briefly considered by Stieglitz (1909), Pia (1932), and others. Their conclusions are summarized below.

Considering a solution in which gypsum and calcite are in equilibrium the following formulae are obtained:

$$CaSO_4 \rightleftharpoons Ca^{++} + SO_4^{=}$$
$$CaCO_3 \rightleftharpoons Ca^{++} + CO_3^{=}$$

The constants of the ionic product (or dissociation) of a solution saturated with gypsum and calcium which are in equilibrium may be expressed:

$$[Ca^{++}]\cdot[SO_4^{=}] = ks \text{ (constant for S)}$$
$$[Ca^{++}]\cdot[CO_3^{=}] = kc \text{ (constant for C)}.$$

The valence of $Ca^{++}$ in both equations is the same, but the required amount of $Ca^{++}$ ions is much greater in calcium sulfate than in calcium carbonate (Pia, 1932, p. 20). From the equation

$$[SO_4^{=}]:[CO_3^{=}] = ks/kc$$

it may be calculated that the amount of sulfate ions in solution must be "about 5000 times greater" (Pia, 1932, p. 20); 4700 times greater (Stieglitz, 1909, p. 250) than that of carbonate ions, in order to maintain the equilibrium.

Under natural conditions the excess of sulfate ions is not so great as required to maintain the equilibrium. Thus, the carbonate precipitates first until the concentration of carbonate ions reaches a ratio 1/5000 that of the sulfate ions (the ratio ks/kc).

When in the solution, which is in equilibrium with both salts, the concentration of the sulfate ions is increased by an addition of a second sulfate (sodium or potassium sulfate), the solution is oversaturated with calcium sulfate and gypsum precipitates. The loss of calcium ions makes the solution undersaturated in regard to the carbonate, and some of the calcium carbonate present must pass into solution until the ratio 1/5000 is reached (Stieglitz, 1909, p. 251). Generally, calcium carbonate precipitates first as pure calcite until the conditions of equilibrium are re-established, and then, with advanced evaporation, a mixture of both calcite and gypsum precipitates.

A precipitation of a mixture of two minerals from solution is theoretically and practically possible (Findlay, 1900, p. 416–417). Under certain circumstances only an easier soluble salt may be precipitated. The separation depends on the constants of equilibrium.

Von Raupach (1952, p. 113) states that in Karabugaz-göl a layer 1 mm thick of sulfate-carbonate sediment is deposited yearly and that the solubility constants of carbonates and sulfates are influenced by the water temperature; sulfates precipitate in winter, and car-

bonates in summer. The yearly banding of the sediments, however, is not due to the turbidity of water. This raises the question of whether temperature may not be more significant than hydrogen-ion concentration in explaining the apparent simultaneous deposition of gypsum and calcite.

The occurrence of calcium carbonate with gypsum, as the cement in siltstones of the Virgin formation, points to a restricted arid environment of deposition, where evaporation exceeded precipitation and inflow. As the evaporites are represented mainly by primary gypsum, and only locally by small percentages of anhydrite, the prevailing temperature during deposition must have been around 30°C, and only occasionally, and then for short periods, above 30°C, when anhydrite precipitated. The very high salinity in the basins limited or even inhibited organic life, and the evaporites were precipitated from saturated solution in the absence of bacteria or higher organisms.

The lagoons did not need to be connected with the open sea, but occasional influx of sea water is possible and may have influenced the equilibrium and solubility of the gypsum and calcite.

During the deposition of the siltstones "$Q_2$", "$T_1$", and "W", environmental conditions did not undergo major changes. Owing to migration of the shore line, the distance of the depositional basin from the sea varied during the deposition of the siltstone of unit "$V_3$". Lenticular conglomeratic layers of fragments of gypsiferous siltstones are embedded in silty gypsum. These layers, marking diastems, may have been formed during storms.

## Sedimentary Structures

### *Bedding*

The stratification of the limestones ranges from shaly to massive. Some of the crystalline limestones are essentially structureless, showing a thin bedding only on weathered surfaces. Most silty limestones exhibit finer bedding than do the less silty ones, and most of the limestones have irregular and uneven bedding. Regularity of bedding seems to be an exception.

The siltstones generally exhibit a uniform shaly and flaggy bedding. A single stratum may range from less than a fraction of an inch to 1 foot 4 inches thick. The bedding of calcareous, gypsiferous siltstones is not well developed; the weathered rock does not show bedding and crumbles very readily. Other weathered siltstones split easily along the bedding planes into thin layers.

### *Cross-Stratification*

A few layers of limestone "A", "C", and "S" are cross-stratified in several localities. Cross-stratification seems to be normal in the uppermost limestone layer of unit "C". This clastic limestone is composed mainly of fragments of fossils. In many localities "torrential" cross-strata dip up to 23° with respect to the original horizontal surface. This limestone may have been built by the action of marine current, much as delta deposits are formed today—the current carrying the shells and their fragments from the shore and depositing them on the consecutively built foreset slopes.

A fine cross-ripple lamination was developed locally in limestones containing interference ripple marks.

Cross-bedding in the siltstones is rare and occurs chiefly on a small scale in association with ripple-marked surfaces (cross-ripple lamination).

### *Graded Bedding*

Graded bedding is common in the gray, calcareous siltstones. These are thinly bedded or laminated, and the bedding is marked by the decrease in size of silt grains from the bottom toward the top of a single lamina.

### *Ripple Marks*

Ripple marks are present on the tops of many siltstones. They are less well developed in the limestones but, where present, they are conspicuous among the primary structures. This is notably the case in units "S", "U", and "V".

Ripple marks are essentially limited to parts of the limestone with considerable silty material and to limestones that are laminated or that have a shaly bedding.

Oscillation ripple marks in the silty lime-

stones of unit "S" probably result from the wave action and are the most persistent ripple marks observed.

Ripple marks in the silty limestones of "U" and "V" are asymmetrical and are interference ripple marks. They were probably built by cross currents or by interaction of waves and currents with the latter currents partly obliterating earlier ripple marks.

A few *Pleurophorus*, and some indeterminate, irregular, tubular forms resembling worm trails, are associated with ripple marks in the limestone of unit "U".

Ripple marks on the top surfaces of most of the siltstones have amplitudes of less than 1 inch. Most are poorly preserved, but molds developed on the lower surfaces of the overlying limestones show that they were formed both by wave- and current action.

### *Mud Cracks*

Mud cracks were observed only in the limestones "A", in sections 1 and 12, and in the limestone "L", in section 6. The layers in which the mud cracks occur are silty near the bottom, and both grain size and silty material diminish toward the top.

The mud cracks in the limestone "A" in section 1 are arranged in an irregular, polygonal network. The cracks are up to 4 inches deep and, where bedding is thin, may affect more than one layer. The cracks range up to 1 inch wide at the top, wedging downward, and are filled by the dark-gray limestone from above.

The mud cracks on the top of limestone P-529 represent a very delicate network. The crack reticulation is very shallow and narrow, but conspicuous.

Mud cracks occur near the top of many siltstones. They are well preserved in only a few places and are not easily detected.

### *Submarine Denudation*

On all exposures of the top of the uppermost limestone of unit "C" a series of parallel grooves trend north-northwest. The grooves are unevenly spaced and are up to 2 inches from crest to trough. In places they are more than 10 inches apart but locally they are crowded. They appear to be parallel. Many striae parallel the grooves. The surface resembles the markings of a fault plane. However, such a fault would have had to occur along an almost horizontal plane, and there are no indications of such a bedding-plane fault.

The writer believes that these grooves and striae result from submarine slumping, before complete induration of the sediments. The slumping may have been started by turbidity currents, the gravity of the sediments, or by an earthquake. Once the equilibrium had been upset, the mass of the sediments would glide over a submarine slope, until it came to rest upon a horizontal sea bottom, or until the turbidity currents that may have been started by the slumping had picked up most of the material from the bottom. This material may be redeposited in the same area or may be transported and redeposited elsewhere.

It seems unlikely that a turbidity current transporting sediments could have formed the grooves. At least they would not have produced parallel grooves over distances observed on the top of the limestone of unit "C". The grooves may have been gouged during submarine slumping of partly solidified muds over the sediments. Heim (1908, p. 142) applied a term "Subsolifluktion" to the sliding of subaqueous sediments. This term was a modification of "solifluction" coined by Andersson (1906, p. 96) in his discussion of subaerial denudation. Heim noted that subaqueous solifluction may occur on slopes with an inclination as low as 2°–3°, although it is most frequent on slopes between 4.4° and 6.0°.

Rettger (1935, p. 276) deformed soft sediments by slump, differential movement, and differential loading. He showed that the mass will begin to slide when the tank is tilted about 7° from horizontal, but in several instances the required gradient was as much as 20°.

Heim (1908), studying subaqueous slumps in the lakes of Switzerland, concluded that "the greater the moving mass (of mud) the smaller the average inclination of the slope" (p. 142) required to start and continue the movement.

The crinoidal limestone of "D" was deposited on bevelled surfaces of the cross-stratification

of "C". The limestone of "D" is missing in sections 3 to 9, and 11, possibly because of "omission" resulting from subaqueous solifluction, or because of subaqueous "dereption." Heim (1924, p. 5) applied the term "omission" to a period of nondeposition and "dereption" to subaqueous denudation by mechanical action of water currents.

It has been impossible to recognize in the field sediments transported by slumping, unless they are represented by the strata that overlie the limestone "C". The crinoidal limestone of "D" that locally overlies the limestone of "C" argues against the foregoing hypothesis. If the crinoidal limestone had slumped, more silty or clayey material would be expected in it.

The most striking example of contorted bedding is an intricate "folding" in siltstone of "P". This greenish-gray unit is composed mainly of quartz grains of medium silt size, cemented by a moderate amount of lime. Many layers of "P" apparently were exposed above the water level for short periods, at least. They contain indeterminate tracks and "shell-and-cast" structure, developed probably during differential desiccation. These structures could have been preserved only where they were covered by silt deposited in quiet water.

The similarity of the structures in "P" to the structures of deformed strata described from other parts of the world and from other formations, by Heim (1908; 1924), Fairbridge (1946), and Kuenen (1948; 1950a; 1950b; 1951) supports the supposition that subaqueous slumping has caused this deformation.

### *Intraformational and Basal Inclusions*

Small, scattered fragments of greenish-gray, yellow-gray, and gray calcareous siltstone are included in the basal parts of several limestone units. They vary in size and shape, are commonly subangular and angular, but some are irregular. They range up to 4 inches in diameter, but the average is less than 1 inch.

The inclusions are locally concentrated along the bedding planes and also occur near the top of the same layer (limestone of unit "L", section 3). The inclusions have been derived from the siltstones directly under the limestones, and the fragments may have been transported but a short distance before being emplaced in limestones.

Siltstone fragments near the bottom of the limestone units, and also ripple marks and mud cracks on the top of the underlying siltstones indicate diastems or intraformational disconformities.

The origin of the siltstone fragments included in the middle part of the limestone, such as the limy siltstone inclusions and those on the bedding planes of limestone units (as in unit "L", section 3), is not certain. The fragments of siltstone may have been rafted on algal holdfasts or in roots of trees, and transported by sea currents into areas of limestone precipitation.

### *Concretions*

In the middle of limestone "A" in section 12 are lenticular concretions of silty limestone, slightly lighter in color than the enclosing rock. These concretions occur in the cross-stratification of the bed.

Other concretions, spherical to almost round, occur in the upper part of the limestones of unit "C", in sections 14 and 17. These range in diameter from 4 inches to 2 feet and are gray, dense, hard, finely crystalline limestone. They occur within a massive limestone layer. The concretions may be recognized by differential weathering on the upper surface of the limestone.

Concretions of various sizes and shapes are present in most of the gray siltstones. They consist of limy siltstone, usually much harder than the surrounding rock, or of silty limestone. The most common are disc-shaped, about half an inch thick, and 1–2 inches in greatest diameter. The bending upward of the laminae in the siltstone around the concretions suggests that they are syngenetic.

Other concretionlike bodies consist of lenticular layers of silty limestone that may have developed as rows of platy concretions united to form a continuous layer.

### *Stylolites*

Stylolites are limited to limestones containing relatively little silty material and having a

finely or coarsely crystalline texture. They are common in several of the limestone layers of "A" and in some of the layers of "C". The limestones of "S" and "X" also contain stylolites locally.

The stylolites occur usually within single limestone layers. In section 15 stylolites occur between layers at the contact of the limestone of unit "C" with that of unit "D". All have up to 4 inches of vertical relief. The space along the stylolites is filled by clayey limestone "residue" that ranges from 3 to 8 mm thick.

All stylolites observed parallel the bedding. They probably were formed after the consolidation of the rock but before structural deformation. There is no evidence for a syngenetic formation of stylolites.

### Cyclic Sedimentation

A repetition of strata is interpreted as a form of cyclic sedimentation, as defined by Weller (1930). Individual cycles in the Virgin formation consist of an alternation of limestone and siltstone. A single cycle is bounded both below and above by an unconformity.

Sea waters are believed to have encroached over broad coastal plains creating favorable conditions for precipitation of limestone. Silty limestones, locally containing inclusions derived from the underlying siltstones, were deposited first. When the turbulence subsided, nearly pure limestones were precipitated. These pure limestones grade upward into very silty limestones that form transitions between the two types of sediment. The influx of silty material continued to form siltstones until the basins were filled. The upper surfaces of siltstones show either subaqueous denudation or subaerial weathering or erosion. With invasion of the sea, a new cycle of deposition began.

Four complete cycles were observed in the lower part of the formation. The lithologic variation appears to be mainly a function of the amount of silt deposited. During periods of no silt deposition, relatively pure limestones developed; as silt influx began and increased, the limestones became more silty until the rock became a calcareous siltstone. In late stages, the silt influx appears to have exceeded the rate of the sinking of the basin of deposition, so that the basin became filled. Most probably, by-passing (Eaton, 1929, p. 714) and nondeposition were important factors. During this interval evidences of erosion suggest diastems of unknown time significance.

The cause of the variation in silt content and hence the reason for cyclical deposition is not known. According to Wanless and Shepard (1936) it may be due to (1) periodicity of tectonic movements, (2) climatic cycles of various lengths, (3) sea-level fluctuation, (4) cyclical shifting of the distributaries of a delta, and (5) periodic volcanism. The last two may be disregarded here for no evidence of deltaic sedimentation or of volcanic activity is available. However, the other causes may have influenced the cyclic sedimentation.

The alternation of silty limestone and calcareous silts with a slight disconformity at the base of limestones, and the lenticular and tabular bodies indicate a neritic type of cyclic sediments (Wanless and Shepard, 1936, p. 1186) and suggest a foreland condition of deposition on a mildly unstable shelf.

### Paleontology

Marine fossils occur in the gray, calcareous siltstones and in the limestone units of the formation. Most of them are very poorly preserved. The best preservation is among large specimens of *Aviculopecten*, but they, as well as most of the other fossils, could be determined only to genera. Most of the fossils in the crystalline limestones are replaced by calcite.

CRINOIDS: Crinoid stems and calyx plates and echinoid spines are in almost every limestone and in many siltstones. Some limestones are almost entirely crinoid fragments (unit "D"), and the fragments form the bulk of the limestones of units "G", "J", "N", "S", "X", and, locally, "L". No complete calices have been found. Girty identified the crinoid fragments collected by Reeside and Bassler (1922, p. 67) as *Isocrinus*.

Crinoids may indicate the depth and temperature of the environment. Crinoids live in temperatures between 25° and 85°F, from very shallow water to the greatest depths, and

in any latitude (Clark, 1931, p. 26–28). However, the family Pentacrinidae, to which the crinoids in unit "D" may belong, require temperatures from 55° to 65°F. This temperature appears to be most convenient for their physiological and ontogenetic development (Clark, 1914, p. 10).

Temperatures ranging from 55° to 65°F are found down to the depth of about 125 fathoms (Kuenen, 1950b, p. 25). Thus, the Virgin formation crinoids may have lived in any depth above 125 fathoms.

BRACHIOPODS: Two groups of brachiopods have been noted in the limestones. Both are relatively well preserved because of their phosphatic shells.

The superfamily Triplesiacea is represented by a form "Pugnax," strongly resembling the genus *Pugnoides*. They are common or abundant in limestones with a small amount of clastic material, units "A", "C", and "G", but are considerably less abundant in units "L" and "N". They were not observed above "N".

A second group belongs to the superfamily Terebratulacea. Specific identification has not been made. These brachiopods are rare to common in the limestones of units "A", "C", "E", and "G" and are abundant in the silty limestones of units "L" and "N". They are especially abundant in the limestone of unit "U".

PELECYPODS: Pelecypods are present in almost every silty marine stratum but were not observed in the lagoonal facies. They are very rare in the crystalline limestones and especially abundant at the top of the silty limestones, notably unit "G", and in limestone layers of unit "V", where they form the bulk of the rock.

In the transitional zone between the limestones and overlying gray siltstones, there is in many places a layer of limy siltstone, 4–8 inches thick, in which large pelecypods, including *Aviculopecten*, are common.

The poor preservation of pelecypods has prevented their specific identification, and their generic identification is only tentative.

The fauna in the limestone units contains large specimens of *Aviculopecten*, *Myalina*, and *?Pseudomonotis*. The smaller pelecypods are represented by *Monotis*, *Bakewellia*, *Pleurophorus*, *?Myophoria*, and dwarfed (?) forms of *?Pseudomonotis* and *Myalina*.

The gray, calcareous siltstones contain many small pelecypods which form about 95 per cent of the fauna in units "F", "I", "O", "Q", and "V". No fossils have been observed in siltstones of units "B" or "T". *Monotis*, *Myalina*, *Pleurophorus*, and *?Pseudomonotis* persist in siltstones of units "F" to "O", while *Bakewellia* is known only from siltstone of unit "F".

GASTROPODS: Preservation of the gastropods is even poorer than that of other fossils. Two forms that may be *Pleurotomaria* and *?Naticopsis* are in the near-shore limestones of the upper part of the formation. A very small gastropod, resembling a small *Valvata*, occurs in the near-shore siltstones of the upper part of the formation.

WORMS: Small, calcareous worm tubes that may be *Spirorbis* have been noted in strata that represent a shallow, marine, near-shore environment. Worm tubes locally are attached to the shells of large *Aviculopecten*. Worm trails of other types occur on top surfaces of the siltstones of probable tidal-flat origin.

CRUSTACEANS: About 3 feet above the base of the siltstone of unit "Q", in section 3, small, poorly preserved crustaceans occur in association with small gastropods (*?Valvata*) and some small, indeterminate pelecypods.

Dr. Leif Størmer of the Paleontologisk Institut Styrer in Oslo, Norway, has identified these crustaceans as *Halicyne*. *Halicyne* has been figured by Woodward (1866–1878), as *Halicyne*, von Meyer, 1847 ("Paleontographica," vol. 1, p. 134) under the name *Halicyne agnota*, and a second species under the name *H. laxa*. *Halicyne laxa* has been collected in the Muschelkalk (Middle Triassic) of Rottweill in Germany.

Ostracods are abundant in some of the calcareous siltstones. They are poorly preserved and have not yet been studied carefully.

CEPHALOPODS: Poorly preserved, fragmentary cephalopods belonging to the subclasses Nautiloidea and Ammonoidea were collected in the lowermost 7 feet of the siltstone of unit "I". All the specimens were collected north of section 14.

The Ammonoidea were examined by Dr.

Siemon Wm. Muller, and most of the specimens were identified as *Tirolites spinosus* Mojsisovics *s. l.* Two specimens were identified as *?Cordillerites* and possibly *?Hungarites*. Regarding *Tirolites spinosus*, Muller observes that "all these species characterize the top of the Werfener beds in the Alps or the top of the Lower Triassic." The other two ammonoids, *Cordillerites* and *Hungarites*, are also characteristic of the upper part of the Lower Triassic.

The Nautiloidea are represented by orthoceratids and are not diagnostic as to the age.

## Age and Correlation of the Virgin Formation

The ammonoids—*Tirolites spinosus* Mojsisovics *s. l.*, *?Cordillerites*, and *?Hungarites*—collected during the present study are the only fossils that indicate the age of the Virgin formation.

The Lower Triassic of North America is divided by Smith (1932, p. 13) into the following ammonite zones:

V. *Columbites* zone
IV. *Tirolites* zone
III. *Meekoceras* zone
II. *Genodiscus* zone
I. *Otoceras* zone.

*Tirolites* in strata about 107 feet below the top of the Virgin formation places the formation definitely in the upper part of the Early Triassic and clearly suggests that some, at least, of the overlying "members" of the Moenkopi group are Middle Triassic.

The only place in the United States where *Tirolites* has previously been found is Paris Canyon, Bear Lake County, Idaho. The *Tirolites* zone there is about 225 feet above the *Meekoceras* zone and 30 feet below the *Columbites* zone (Smith, 1932, p. 18). Kummel (1943, p. 322) confirms the conclusions of Smith.

The *Tirolites*-bearing strata of the Virgin formation appear to be correlative with the *Tirolites* limestone of the Thaynes formation in the Bear Lake area of southeastern Idaho. They also may be correlated with the Campil beds of Tyrol (Smith, 1932, p. 18; Mojsisovics, 1882, p. 64–75) and with upper Werfener strata of the other Mediterranean localities of the Triassic provinces (Kittl, 1903, p. 1–10).

## Depositional History of the Virgin Formation

The lithology, sedimentary structures, and stratigraphic sequence of the Virgin formation permit the following interpretation of its depositional history.

Post-Kaibab, pre-Moenkopi warping and erosion formed deep valleys in the gypsiferous siltstones and the limestones of the alpha member of the Kaibab formation. The two lowest "members" of the Moenkopi group in the St. George area—the Timpoweap "member" and the lower red "member"—were deposited on this eroded surface. The Rock Canyon conglomeratic strata filled channels, some of which were 250 feet deep (Reeside and Bassler, 1922, p. 60), in the Kaibab limestone.

The siltstones of the lower red "member" of the Moenkopi group were deposited apparently without break in sedimentation on the Rock Canyon conglomeratic "member" and, locally, on the gypsiferous strata of the alpha member of the Kaibab. These siltstones, which appear to have been deposited under lagoonal conditions, may have covered the gypsiferous alpha member of the Kaibab.

After deposition of the lower red "member" erosion developed a topography characteristic of late maturity. Locally, channels may have been cut through to the alpha member of the Kaibab.

The Virgin formation formed as the sea advanced to develop relatively quiet embayments across the extensive rolling topography of the lower red "member." Lensing, and a lack of uniform thickness in single strata of the lower portion of unit "A", are a result of the uneven surface upon which they were deposited.

The absence of a basal conglomerate and the presence, in its place, of considerable clastic material in the lowermost limestone stratum of unit "A" suggest that only well-weathered regolith was present on the erosion surface and that the surrounding lands were low and deeply weathered, furnishing little coarse debris. The presence of only scattered, angular, and subangular fragments of the lower red "member" as inclusions in the basal stratum of unit "A" suggests that wave action in the

advancing sea was not sufficiently strong to do much more than rework the regolith and did not seriously attack the unweathered deposits beneath it.

Occasional mud cracks on some of the lowermost limestone strata of unit "A", and local cross-stratification of deltaic type, also confirm that the sea advanced as very shallow embayments over a relatively flat surface. Slight elevations on this surface may have limited the embayments and deflected currents and waves sufficiently to cause the cross-stratification. The mud cracking probably was caused during low tides when the sea withdrew from extensive areas of the shallower embayments.

Subsidence appears to have been slow but continuous, and by the time the lower half of unit "A" had been deposited the irregularities of the initial basin of deposition had been buried. The persistence of the upper part of the unit testifies to the regularity of the floor of deposition, and the lack of silt indicates deposition in clear waters.

The clear, quiet waters permitted the immigration and development of terebratulid brachiopods. Percival's studies (1944) of recent *Terebratella* have shown that they require relatively quiet waters and a firm substratum, covered only with a thin film of organic debris for feeding.

The fragments of crinoids in the limestones of a part of unit "A" containing brachiopods support the theory of quiet water. The crinoids probably did not live far from the place of burial.

During the deposition of the siltstone of unit "B", an influx of clastic material filled the depositional basin to base level. The surface of the siltstone was exposed to waves and currents, as evidenced by the interference ripple marks and by local erosion. This ended one cycle of deposition.

A new cycle began with the deposition of the limestones of unit "C". The lowermost limestones contain considerable silt. This may have been derived from the reworking of the uppermost layers of unit "B" or may have come from a source outside the basin.

The silt content diminished rapidly with the progress of sedimentation, and limestones of the upper part of unit "C" contain only scant silty material. The limestone directly below the top layer contains abundant fragments of crinoids. This limestone is strongly cross-stratified, showing "torrential" cross-bedding. It may have been formed from crinoid fragments driven by sea currents and deposited on a slightly inclined slope of a shallow sea floor, similar to the way deltas are built.

The upper surface of the limestone of unit "C" is grooved and striated. These grooves may have been formed by sliding of overlying, not entirely consolidated sediments. It is not possible to determine what strata, if any, are missing. The sediments may have been transported a long distance.

Subsequent to the grooving of the upper surface of unit "C" there was a period of little influx of detrital material when the crinoidal limestone of unit "D" was formed. Such a limestone required clear sea water and the action of waves or currents to transport and sort the material.

The increase of silty material in the limestone of unit "D" to the southeast suggests that the source must have been in that direction.

Renewed influx of detrital silty material resulted in the deposition of unit "F". The laminae of the siltstones show a slightly graded bedding, suggesting possible seasonal changes controlling the influx of clastic material.

The increase in lime and in the thin layers and laminae with ripple marks toward the top of the unit "F" and mud cracks on the top of the uppermost siltstone indicate a shoaling of the depositional basin and exposure to atmospheric action, probably as tidal flats. The occurrence of fragments of this unit in the lowermost limestone of the overlying unit "G" testifies to slight erosion of the exposed surface of unit "F" before the deposition of unit "G".

The thin, chemically precipitated, lowest limestone of unit "G" indicates that a third cycle began with an influx of clear marine water. Overlying the basal, essentially non-silty layer are very silty limestones. Wave action left ripple marks on the uppermost surface.

During the deposition of the limestones of unit "G" the amount of silty material increases in some places from the bottom to the top of a single layer, while in other localities the lower part of the same layer contains more silt than its upper part.

Conditions during the deposition of the siltstones of unit "I" were very similar to those of "F". In addition to a dwarfed pelecypod fauna, a few cephalopod genera (*Tirolites*, *?Cordillerites*, *?Hungarites*, and some *"Orthoceras"*) inhabited this area during the deposition of the lowest part of the siltstones.

Near the end of the deposition of the siltstones of unit "I", thin layers of silty limestones were deposited locally. The depositional basin was again almost filled as evidenced by interference ripple marks.

A difference in thickness of the siltstones of unit "I" in various localities may have been caused by an uneven distribution of silty material during deposition, by varying erosional conditions at the end of deposition, or by slight post-depositional tectonic movements. There is no field evidence for any crustal movements, and the other hypotheses seem more likely.

Units "L", "M", "N", and "O" represent a fourth depositional cycle. This cycle differs from those below in that silt influx early in the cycle resulted in the highly calcareous siltstone unit "M", rather than silty limestones, such as in unit "G". The limestone of units "L" and "N", underlying and overlying "M", represents the normal, basal facies of the typical cycle.

The vertical and lateral variation in silt content in the limestones of "L" and "N" indicate local variation of the turbidity of sea water. This may be due to the uneven distribution of silty material either by streams or by sea currents.

The local abundance of crinoid fragments and terebratulid brachiopods in the crystalline parts of the limestones "L" and "N" indicates quiet but relatively shallow water. Pelecypods —mainly *Myalina*, *Monotis*, and *Pseudomonotis*—are rare in the crystalline limestones but increase in the silty limestones of the same unit.

An influx of silt near the end of deposition of limestone "N" marks the transition to unit "O".

Rhythmic, graded bedding in the laminated siltstones of unit "O" suggests seasonal (?) changes that affected the influx of silty material. Common ripple marks indicate shallow-water conditions for the lower part of the siltstones. Generally, silt increases gradually toward the top of the unit, where most of the deposits are laminated. The absence of ripple marks suggests quiet-water deposition.

Indeterminate tracks and raindrop imprints on the top of the uppermost siltstone of unit "O" indicate that at the end of the siltstone deposition the basin must have been filled. Withdrawal of the sea locally exposed the sediments to atmospheric action.

Cyclic sedimentation characterizes all the deposits through unit "O". Another cycle started with the deposition of the limy siltstone of unit "P". Unit "P" clearly demonstrates changing conditions in the source area and to some extent forecasts changes in the depositional basin that control the nature of the overlying units "Q", "$Q_1$", and "$Q_2$".

The siltstones of unit "P" are highly calcareous and show rhythmical alternation of thin beds and laminae of fine with somewhat coarser-grained siltstone. Locally, the strata are cross-ripple laminated, and diastems are numerous.

The siltstones of unit "P" are very contorted, strongly folded, and intricately crumpled by preconsolidation slumping. The deformation of the layers persists throughout the area. The underlying and overlying strata have not undergone similar deformation.

The siltstones of unit "P" clearly suggest shallow-water deposition with possible seasonal variation controlling the size distribution and amount of silty material entering the basin. Worm trails and raindrop imprints indicate that the top of the siltstone was exposed to subaerial weathering, probably as tidal flats.

The siltstones of units "Q" and "$Q_1$" are only in sections north and northwest of section 11. In section 11, and in all sections to the southeast, the gypsiferous siltstones of unit "$Q_2$" replace them in the sequence.

The abrupt change in lithology indicates that a barrier, probably a sand bar, was formed

directly north of section 11. This bar resulted in the formation of lagoons to the southeast. The water in the lagoons was subject to excessive evaporation, resulting in the precipitation of gypsum in the beds. Northwest of the bar, however, shallow marine conditions persisted during the deposition of unit "Q" and "$Q_1$". "Red" coloration of the siltstones of unit "$Q_1$" suggests deposition under conditions that permitted at least partial oxidation of ferrous oxides. The coprolitic siltstones of unit "R", known only from section 1, were also deposited in shallow sea.

A disconformity at the top of the coprolitic siltstones of unit "R" in section 1, at the top of the siltstones of unit "$Q_1$" in section 2 to 8, and at the top of the siltstones of unit "$Q_2$" in sections 11 and 12 suggests extensive erosion.

Renewed subsidence of the depositional basin resulted in a southeastward migration of the bar to a position slightly to the north of section 14. At the same time the typical sedimentary cycles were again initiated in the marine areas of deposition. The basal calcareous strata of the new cycle are represented by crystalline limestones of unit "S". These limestones contain a considerable amount of crinoid fragments and a small amount of silty material which indicate shallow, clear, and warm-water conditions.

The overlying siltstone of this fifth cycle is represented by the siltstones of unit "T". As these filled the basin, the bar shifted again, for a short period, to a position north of section 11.

A new, slight subsidence again caused the retreat of the bar, and the limestone of unit "U", in the sections north of 14, and siltstones with the thin layers of limestone, unit "V", were deposited.

As this cycle was completed with the filling of the basin, the shore line migrated northwest, and gypsiferous siltstone (unit "$V_1$") was deposited. The sediments indicate arid conditions.

Local conglomeratic lenses, unit "$V_2$", indicate that the basin was filled at the end of the fifth cycle and subject to erosion.

The limestones of unit "X" overlying the gypsiferous deposits throughout the whole region represent the final marine invasion of the area. These limestones suggest chemical precipitation. Crinoid fragments, locally present, point to shallow, warm-water conditions.

A general emergence, or a much increased rate of sedimentation, caused the sea to withdraw toward the west or northwest. This marked the end of deposition of the Virgin formation in the area and initiated the sedimentary environment in which the middle red "member" of the Moenkopi group was deposited.

## Description of Selected Measured Sections

| Unit | | Thickness (Feet) |
|---|---|---|
| | *Section 1* | |
| | Top of hill; recent erosion surface | |
| | Virgin formation: | |
| S | Limestone, P-449, gray and yellowish gray; locally siliceous; beds 1–4 inches; alternating with calcareous siltstone laminae; silicified fossils.... | 5.3 |
| | Limestone, light gray; silty, laminated and cross ripple-laminated; disc-shaped cherty concretions up to ½ inch in diameter..... | 1.6 |
| | Limestone, P-448, light gray, silty, shaly; finely cross-laminated; beds up to 2 inches thick; alternating with calcareous siltstone, yellow gray; beds up to 1 inch thick; calcareous siltstone inclusions up to ½ inch in diameter at base..... | 2.0 |
| | Disconformity: no relief | |
| R | Siltstone, P-443-446, yellow gray; slightly calcareous; coprolitic; laminated; porous; small gastropods..... | 2.3 |
| | Siltstone, yellow gray; slightly calcareous; laminated and cross ripple-marked; alternation of hard and soft beds ½ to 2 inches thick..... | 10.0 |
| | Siltstone, P-442, brown and yellow gray; slightly calcareous; laminated; molds of indeterminate pelecypods..... | 2.3 |
| | Disconformity: contact flat, no relief | |
| $Q_1$ | Siltstone, P-441, brownish dark gray; slightly calcareous; laminated, ripple-marked; yellow-gray siltstone laminae near the top..... | 18.6 |
| P | Siltstone, P-440, gray, greenish gray; calcareous; laminated and flaggy; locally ripple-marked; middle part of unit crumpled and contorted owing to subaqueous slumping; indeterminate pelecypods, worm trails, raindrop imprints..... | 9.2 |
| O | Siltstone, P-92-94, gray to dark gray; | |

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|---|---|---|
| | calcareous; weakly laminated; poorly preserved pelecypods, ostracods | 10.6 |
| N | Limestone, P-439, greenish gray; very silty; abundant *Aviculopecten, Myalina, Bakewellia* | 0.2 |
| | Limestone, P-438, dark gray; silty near the top; brachiopods, pelecypods; crinoid fragments | 0.8 |
| | Limestone, P-436-437, gray to yellow gray; laminated to flaggy; angular and subangular siltstone fragments near the top and at the base; inclusions up to 4 inches in diameter; abundant crinoid fragments, indeterminate pelecypods and brachiopods | 1.6 |
| | Disconformity | |
| I | Siltstone, P-80-86, 433A-435, gray and brownish gray; calcareous; the uppermost 2 inches not calcareous; laminated, and cross ripple-laminated; thin, irregular lenses of silty limestone; pelecypods and small gastropods near the top; *Tirolites spinosus* Mojs. *s. l.*, *?Cordillerites, ?Hungarites, "Orthoceras"* in the lowermost 6 feet; ostracods | 42.0 |
| G | Limestone, P-75, light olive green; silty; crinoid fragments, *Aviculopecten, Bakewellia, Myalina*, worm trails | 0.3 |
| | Limestone, P-76, gray; finely crystalline; near the bottom silty and with silty limestone inclusions up to 1 inch in diameter; very fossiliferous | 0.5 |
| | Limestone, P-77, gray, thin, irregular beds; many fossils replaced by calcite | 0.7 |
| | Limestone, P-78, 431, gray, slightly silty; massive; abundant crinoid fragments; few mollusks; stylolites 2 inches below the top | 2.3 |
| | Limestone, P-79, 432, gray; crystalline; massive; weathers into "concretions" | 0.8 |
| | Disconformity | |
| F | Siltstone, P-430, gray, dark gray; calcareous; with irregular lenses of silty limestone; ripple marks, interference ripple marks at the top; poorly preserved *Monotis, ?Pseudomonotis, Bakewellia, ?Pleurophorus*, worm trails | 50.0 |
| E | Limestone, P-457, yellowish gray; silty, grades into overlying siltstone P-430; crinoid fragments, small gastropods common; pelecypods and brachiopods common to rare | 1.6 |
| D | Limestone, P-455, crinoidal; light gray to white; massive; indeterminate mollusks; overlying the bevelled limestone P-456 | 3.0 |
| C | Limestone, P-456, gray; dense, crystalline; "torrential" cross-stratification· single bed 6 to 12 inches thick; upper surface bevelled; abundant crinoid fragments; indeterminate pelecypods, locally terebratulids and *"Pugnoides"* common | 4.6 |
| | Disconformity: here covered by talus | |
| B | Slope covered by talus | 17.0 |
| A | Limestone, P-453-454, gray; crystalline; massive; many stylolites; crinoid fragments, and indeterminate pelecypods and brachiopods | 6.4 |
| | Limestone, P-452, gray; crystalline, with silty laminae; bedding irregular; mud cracks at the top | 1.6 |
| | Limestone, P-451, light yellow; crystalline, locally silty; laminated and ripple-marked | 0.8 |
| | Limestone, P-450, light gray and gray; siltstone inclusions up to 4 inches in diameter; satinspar in veins | 0.6 |
| | Unconformity: moderate relief of surface | |
| | "Lower red member" of Moenkopi group | |

*Section 3*

| | | |
|---|---|---|
| | Top of hill; recent erosion surface | |
| | Virgin formation: | |
| S | Limestone, P-72, gray; dense, crystalline; crinoid fragments abundant | 1.3 |
| | Limestone, P-71, light green gray; dense; indeterminate fossils near the top | 0.6 |
| | Limestone, gray and olive gray; silty; massive; showing lamination on weathered surface; ripple marks on top; indeterminate mollusks | 5.3 |
| | Limestone, yellow gray; silty | 0.6 |
| | Limestone, P-70, olive gray; silty; laminated, locally cross-stratified, ripple-marked; porous; near the top almost pure limestone; indeterminate fossils | 4.2 |
| | Disconformity: distinct | |
| $Q_1$ | Siltstone, P-510, greenish gray; limy; top ripple-marked, locally showing slight relief | 0.8 |
| | Siltstone, P-509, brown, very slightly limy, laminated, locally ripple lamination; satinspar in veins | 9.8 |
| Q | Siltstone, P-506, greenish gray; limy; cross ripple lamination; small, indeterminate pelecypods, small gastropods, *Halicyne* common | 0.6 |
| | Siltstone, P-505, dark gray; limy; laminated; small indeterminate mollusks, ostracods | 2.2 |
| P | Siltstone, greenish gray; limy; middle part deformed by subaqueous slumping; ripple lamination | 6.0 |
| O | Siltstone, P-503, gray, limy, laminated | |

| | | |
|---|---|---|
| | and ripple-marked; irregular lenses of silty limestone; *Aviculopecten*, *Myalina*, ?*Pseudomonotis* | 16.3 |
| N | Limestone, P-501, 502, green gray, very silty; bedding uneven; abundant terebratulids; *Myalina*, *Monotis*, ?*Pseudomonotis* rare | 0.8 |
| | Limestone, P-500, green gray; terebratulids abundant | 0.2 |
| | Disconformity | |
| M | Siltstone, P-499, gray, limy; lenses of silty limestone near the top; Terebratulas common, "*Pugnoides*" rare | 1.2 |
| | Siltstone, P-498, green gray, limy; inclusions of siltstone up to 2 inches in diameter, terebratulids | 0.2 |
| L | Limestone, P-496, green gray, silty; small inclusions of siltstone on bedding; terebratulids common | 0.3 |
| | Siltstone, P-495, 497, green, very limy; terebratulids and "*Pugnax*" abundant | 0.2 |
| | Limestone, P-493, 494, gray, slightly silty; structureless; crinoid fragments locally abundant, terebratulids abundant, small gastropods common, ?*Spirobis*, ?worm trails | 1.3 |
| | Limestone, P-492, green gray, very silty; interference ripple marks on top; ostracods | 0.6 |
| | Limestone, P-491, dark gray; silty; structureless; ostracods | 1.0 |
| | Limestone, P-490, green gray; silty; ostracods | 0.3 |
| | Limestone, P-486-489, gray; silty; flaggy, irregular; very fossiliferous at the top | 0.5 |
| | Disconformity: slight relief | |
| I | Siltstone, P-64, 485, 507, gray; shaly, fissile; irregular thin lenses of silty limestone; ripple marks; *Pleurophorus*, *Bakewellia*, *Myalina*; in the lowermost 7 feet *Tirolites spinosus*, ?*Cordillerites*, ?*Hungarites* | 41.6 |
| G | Limestone, P-484, greenish gray, silty; very abundant pelecypods | 0.5 |
| | Limestone, P-483, gray; dense; irregular shaly; crinoid fragments abundant, *Aviculopecten* and *Myalina* rare | 0.8 |
| | Limestone, P-482, olive gray; silty; irregular bedding; crinoid fragments abundant, indeterminate brachiopods | 2.0 |
| | Limestone, P-481, gray, silty; irregular shaly; brachiopods | 0.5 |
| | Limestone, P-480, gray, massive; brachiopods replaced by calcite | 2.0 |
| | Disconformity: very slight relief | |
| F | Siltstone, P-57, gray, calcareous; shaly, fissile; irregular lenses of silty limestone; *Monotis*, ?*Pseudomonotis*, *Pleurophorus*, *Bakewellia* | 46.6 |
| C | Limestone, P-49-52, gray, locally silty; pronounced "torrential" cross-stratification; upper surface bevelled; stylolites; crinoid fragments abundant to common | 4.0 |
| | Disconformity: a slight relief | |
| B | Siltstone, brownish gray, limy (slope covered by talus) | 9.0 |
| A | Limestone, P-53, gray, crystalline; silty at the base; massive; crinoid fragments common, Terebratulas rare to common | 2.6 |
| | Limestone, P-54, gray, crystalline, dense; thick-bedded; rare, indeterminate fossils replaced by calcite | 3.6 |
| | Limestone, P-55, dark gray, silty; laminated | 2.2 |
| | Limestone, P-56, olive gray, very silty; laminated; limy siltstone inclusions in the lowest layer | 1.0 |
| | Unconformity: moderate relief | |
| | "Lower red member" of the Moenkopi group | |

*Section 6*

| | | |
|---|---|---|
| | Top of hill; recent erosion surface | |
| | Virgin formation: | |
| X | Limestone, P-551, white gray, silty; irregular siliceous thin layers; bedding shaly, eneven; small gastropods, probably Pleurotomariidae | 6.6 |
| | Disconformity: slight relief | |
| $V_2$ | Siltstone, P-550, gray, limy, shaly; satinspar in veins and on bedding planes | 1.6 |
| $V_1$ | Siltstone, P-549, brown, slightly limy; thin-bedded and laminated; alternates with green-gray limy siltstone; satinspar mainly in veins | 14.3 |
| V | Silstone, P-548, green gray; calcareous; uppermost 10 inches coprolitic | 8.2 |
| U | Limestone, P-547, gray, silty; laminated; alternates with limy siltstone laminae; ripple marks; ?*Pseudomonotis*, *Aviculopecten* | 2.8 |
| T | Siltstone, P-546, gray, limy; locally laminated | 12.3 |
| S | Limestone, P-545, light gray, silty; laminated; uppermost 10 inches are white gray, with fossils replaced by calcite | 3.8 |
| | Limestone, P-544, gray; dense; massive | 2.0 |
| | Limestone, P-543, dolomitic, yellow gray; silty; laminated and ripple-marked | 0.2 |
| | Disconformity: very slight relief | |

| | | |
|---|---|---|
| $Q_1$ | Siltstone, P-542, light gray; limy; laminated; locally ripple-marked | 0.3 |
| | Siltstone, P-541, brown, limy; laminated and ripple-marked; alternating with green gray, limy siltstone laminae | 15.5 |
| Q | Siltstone, P-540, green gray, limy; laminated and ripple-marked; small gastropods | 2.2 |
| P | Siltstone, P-537-539, gray, limy; intricately folded; "shell and cast" structure, locally ripple-marked; deformation due to subaqueous slumping | 2.5 |
| O | Siltstone, P-536, gray, limy, micaceous; laminated and locally ripple-marked | 5.3 |
| | Siltstone, P-535, gray, limy, micaceous; thin- and thick-bedded; ripple marks common the the upper part | 11.3 |
| N | Limestone, gray, silty, laminated and ripple-marked; alternating with limy siltstone laminae; very poorly preserved mollusks | 1.0 |
| | Limestone, P-533, olive gray, silty; irregular thin-bedded and ripple-marked; poorly preserved pelecypods | 0.3 |
| | Disconformity: slight relief | |
| M | Siltstone, P-532, dark gray, limy; laminated; ripple marks on top; terebratulids and *Aviculopecten* rare to common | 1.0 |
| L | Limestone, P-530, 531, 534, gray; silty; irregularly laminated; *Myalina*, *Aviculopecten*, terebratulids, abundant | 0.6 |
| | Limestone, P-529, gray, crystalline; irregular inclusions of siltstone at the base; mud cracks up to 4 inches deep and up to 1 inch wide, at the top; crinoid fragments abundant, some pelecypods | 0.8 |
| | Disconformity: slight relief | |
| K | Siltstone, P-528, dark gray brown, limy; laminated; uppermost 4 inches gray green and with ripple marks | 2.3 |
| J | Limestone, P-527, gray; silty; poorly preserved pelecypods | 0.3 |
| I | Siltstone, P-525, gray, limy; laminated and thin-bedded; thin lenses of gray silty limestone; *Tirolites* in the lowermost 6 feet | 20.8 |
| G | Limestone, P-521-524, gray, crystalline; locally silty and coprolitic; massive; locally ripple-marked; stylolites; crinoid fragments abundant; very silty and very fossiliferous in the uppermost 7 inches, *Pleurophorus*, *Monotis*, *Pseudomonotis*, *Myalina*, *Bakewellia*, *Aviculopecten* | 4.5 |
| | Limestone, P-520, gray; ripple-marked and silty in the upper part; poorly preserved pelecypods, mainly ?*Pleurophorus* | 0.6 |
| | Limestone, P-519, green gray, very silty; irregular, thin bedding, ripple marks at the top; poorly preserved *Monotis*; ostracods | 0.8 |
| | Limestone, P-518, gray, crystalline; massive, ripple-marked near the top; *Pseudomonotis*, *Monotis*, most common near the top; small siltstone inclusions at the base | 0.6 |
| | Disconformity: slight relief | |
| F | Siltstone, P-514-517, gray; brown gray in the upper 6 feet, green gray uppermost 4 inches; limy throughout, with gray silty limestone thin, irregular lenses; laminated and ripple-marked; interference ripple marks at the top; *Monotis*, *Myalina*, ?*Pseudomonotis*, *Bakewellia*, ?*Pleurophorus* | 47.3 |
| C | Limestone, as unit "C" in section 1 and 3, with bevelled upper surface | |

*Section 7*

| | | |
|---|---|---|
| | Top of hill; recent erosion surface | |
| | Virgin formation: | |
| T | Siltstone, green gray, limy; exposed about | 6.0 |
| S | Limestone, gray and olive gray, silty; thin-bedded | 3.5 |
| | Limestone, P-158, gray, crystalline, massive | 2.5 |
| | Disconformity: not pronounced here | |
| $Q_1$ | Siltstone, brown gray, limy | 9.0 |
| | Siltstone, gray, limy | 13.5 |
| P | Siltstone, gray to green gray, limy; intricately folded due to subaqueous slumping | 2.5 |
| O | Silstone, gray and brownish gray, limy, laminated | 22.8 |
| N | Limestone, gray, silty, laminated | 1.0 |
| M | Siltstone, P-153-157, green gray; laminated; fossiliferous | 1.3 |
| | Disconformity: not apparent here | |
| L | Limestone, P-150-152, gray, massive; silty near the top; abundant crinoid fragments, pelecypods common | 1.6 |
| | Disconformity: slight relief | |
| K | Siltstone, gray, limy; laminated; uppermost 4 inches green gray | 2.0 |
| J | Limestone, P-149, gray; green-gray, limy siltstone laminae on bedding; poorly preserved fossils; this limestone lenses out southward | 0.3 |
| I | Siltstone, P-161-165, gray, limy; laminated and ripple-marked | 20.6 |
| G | Limestone, P-138-147, gray; crystalline, massive; silty and thin, irregularly bedded at the top, in the middle, and at the base; crinoid fragments abundant; other fossils indeterminate | 4.5 |

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|---|---|---|
| | Disconformity: slight relief | |
| F | Siltstone, dark gray, limy; green gray at the top; slope covered | |

*Section 8*

| | | |
|---|---|---|
| | Top of hill; recent erosion surface | |
| | Virgin formation: | |
| X | Limestone, white, porous; irregularly laminated; locally silty and siliceous | 5.8 |
| | Disconformity | |
| $V_1$ | Siltstone, brown gray, slightly limy; gypsiferous; satinspar in veins | 17.0 |
| V | Siltstone, P-176, green gray, limy | 9.0 |
| U | Limestone, gray, crystalline; laminated and ripple-marked; with laminae of silty limestone; poorly preserved fossils | 2.6 |
| T | Siltstone, greenish gray, limy, laminated | 14.0 |
| S | Limestone, P-173-175, 177-178, gray; silty at the top; fossiliferous | 1.7 |
| | Disconformity: very slight relief | |
| $Q_1$ | Siltstone, dark brown gray, slightly limy; with gray limestone lens near the top, and with 4 inches of gray, limy siltstone at the top | 7.2 |
| Q | Siltstone, gray, limy; laminated | 10.0 |
| P | Siltstone, gray to greenish gray, limy, micaceous on bedding; intricately folded due to subaqueous slumping | 2.3 |
| O | Siltstone, gray, limy; laminated; ripple marks common | 17.7 |
| N | Limestone, P-171-172, greenish gray; silty on bedding; fossiliferous | 0.3 |
| M | Siltstone, gray, limy; laminated | 0.4 |
| L | Limestone, P-169-170, green gray, silty; fossiliferous | 0.2 |
| | Siltstone, green gray, limy | 0.2 |
| | Limestone, P-166-168, gray, dense; massive; locally porous; crinoid fragments abundant; brachiopods and pelecypods common | 3.5 |
| | Disconformity: slight relief | |
| I | Siltstone, gray, limy; irregular laminae, ripple marks throughout, especially at the top; in the lowermost 6 feet poorly preserved cephalopods | 21.0 |
| G | Limestone, like unit "G" in section 7; fossiliferous | 4.6 |
| | Disconformity: slight relief | |
| F | Siltstone, dark gray, limy; with silty limestone nodules; worm trails | 8.3 |
| | Limestone, P-192, gray, silty; fossiliferous; lenticular layer | 0.1 |
| | Siltstone, gray, limy; with silty limestone thin lenses and small irregular concretions; poorly preserved pelecypods and small gastropods | 31.3 |
| C | Limestone, P-193-196, gray, silty; fossiliferous; lower part covered by talus; exposed only | 0.6 |

*Section 10*

| | | |
|---|---|---|
| | Top of hill; recent erosion | |
| | Virgin formation: | |
| D | Limestone, P-257-260, gray, crystalline; stylolites; abundant crinoid fragments | 3.8 |
| C | Limestone, P-253-256, gray, fine to coarse crystalline; poorly preserved brachiopods; the bottom irregular | 2.7 |
| | Disconformity along pronounced stylolites | |
| A | Limestone, P-252, gray, silty; poorly preserved fossils | 0.4 |
| | Limestone, P-251, gray, crystalline; thick-bedded | 1.5 |
| | Limestone, gray, silty; thick-bedded | 2.3 |
| | Limestone, P-248-250, gray, silty; almost pure limestone in the upper part; thin- and thick-bedded | 5.2 |
| | Unconformity | |
| | "Lower red member" of the Moenkopi group | |

*Section 11*

| | | |
|---|---|---|
| | "Middle red member" | |
| | Virgin formation: | |
| Y | Siltstone, P-297, siliceous, to silty chert, white; almost structureless; small mollusks, indeterminate | 0.6 |
| X | Limestone, P-293–296, gray; dense, crystalline; silty in the middle of the layer; thin-bedded; irregular bedding near the bottom; fossils replaced by calcite; galena crystals disseminated; base irregular | 5.0 |
| | Disconformity: slight relief | |
| $V_2$ | Limestone, P-292, light gray to white; laminated, ripple-marked, and locally cross-bedded; alternates with laminae of limy siltstone; inclusions of gypsum up to 5 mm. in diameter | 3.6 |
| | Disconformity: slight relief | |
| $V_1$ | Siltstone, dark brown; locally gypsiferous | 12.6 |
| V | Siltstone, P-290-291, gray, limy; alternates with green-gray, silty limestone 1–4 inches thick lenticular layers; ripple-marked; poorly preserved mollusks | 11.6 |
| U | Limestone, P-289, gray, silty; massive; ripple marks at the top | 0.6 |

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|---|---|---|
| $T_1$ | Siltstone, brown gray, gypsiferous; greenish in the uppermost 10 inches | 3.3 |
| | Gypsum, greenish gray, silty; thin, irregular bedding | 0.6 |
| | Siltstone, light greenish gray; gypsiferous, silty; nearly structureless | 2.5 |
| | Siltstone, gray, gypsiferous; irregular layers | 2.0 |
| T | Siltstone, P-288, gray, limy; conchoidal fracture | 1.6 |
| S | Limestone, P-287, gray, dense, massive; fossils replaced by calcite | 0.8 |
| | Limestone, P-287, gray, silty; laminated; locally cross-stratified; small limy concretions | 1.6 |
| | Disconformity: slight relief | |
| | Siltstone, P-286, greenish gray; laminated; locally cross-laminated; banded with gray, gypsiferous siltstone; satinspar in fractures | 2.8 |
| $Q_2$ | Siltstone, P-285, brown; gypsiferous; laminated; satinspar; gypsum laminae in uppermost 3 feet | 15.0 |
| P | Siltstone, P-284, gray, limy; laminated; ripple marks; locally deformed by subaqueous slumping | 5.0 |
| O | Siltstone, P-283, dark gray; limy; laminated; locally cross ripple-laminated | 16.6 |
| N | Limestone, P-278-282, gray; massive; very silty at the top; crinoid fragments, terebratulids, *"Pugnoides"* abundant; *Myalina*, *Aviculopecten* common to abundant | 1.8 |
| | Disconformity: slight relief | |
| $I_1$ | Siltstone, brown gray; laminated | 6.6 |
| I | Siltstone, P-277, dark brownish gray; limy, micaceous on bedding, laminated; *Tirolites spinosus*, *"Orthoceras,"* in the lowest 6 feet; other mollusks very poorly preserved | 13.3 |
| G | Limestone, P-267-268, gray, crystalline, slightly silty; thin, irregular bedding; fossils replaced by calcite | 1.3 |
| | Limestone, P-269, gray, crystalline; "torrential" cross-bedding; greenish gray siltstone small inclusions | 1.6 |
| | Limestone, P-270-271, gray, crystalline; locally silty; massive; crinoid fragments abundant, ?worm trails | 1.8 |
| | Limestone, P-272-273, gray; silty, locally crystalline; thick-bedded; crinoid fragments common, brachiopods and pelecypods rare, poorly preserved; the thickness varies within a few yards | 2.9 |
| | Disconformity | |
| F | Siltstone, P-274, dark gray, slightly limy; laminated; the uppermost 8 inches are green gray, with brown gray layer 1 to 2 inches thick on top | 5.0 |
| | Siltstone, P-275, green gray, limy; micaceous on bedding; irregular small nodules of limy, hard siltstone up to 4 inches in diameter, and limy siltstone inclusions up to 1 inch in diameter; laminated and cross ripple-laminated | 1.6 |
| | Siltstone, dark gray, limy; micaceous on bedding; poorly preserved *Bakewellia*, *Pleurophorus*, *Myalina*, few *Aviculopecten* | 29.0 |
| C | Limestone, P-265, gray; silty; cross-ripple lamination in the upper part; crinoid fragments abundant, pelecypods common | 0.8 |
| | Limestone, P-264, gray, crystalline; crinoid fragments abundant | 0.5 |
| | Disconformity: here not apparent | |
| B | Siltstone, brownish gray; slope covered by talus | 9.3 |
| A | Limestone, P-261, gray; thin-bedded; brachiopods replaced by calcite | 0.9 |
| | Limestone, P-262, gray; "torrential" cross-stratification; porous in the middle of the layers; fossils indeterminate, replaced by calcite | 2.4 |
| | Limestone, P-263, gray, crystalline; only upper part exposed | 1.3 |
| | Contact with underlying strata covered by talus | |
| | Unconformity: here covered by talus | |
| | Alpha member of the Kaibab formation | |

*Section 12*

| | | |
|---|---|---|
| | "Middle red member" of the Moenkopi group | |
| | Virgin formation: | |
| Y | Siltstone, P-343, light gray; siliceous and limy; almost a silty chert; indeterminate mollusks | 0.6 |
| X | Siltstone, P-344, 479, white, limy; with indeterminate pelecypods and brachiopods | 1.8 |
| | Disconformity: moderate relief | |
| $V_3$ | Siltstone, P-342, white; limy, gypsiferous; alternates with lenticular layers of silty gypsum; the thickness of gypsum layers increases upward; siltstone fragments embedded in gypsum | 10.8 |
| | Disconformity: moderate relief | |
| $V_1$ | Siltstone, P-341, dark brown; slightly limy gypsiferous, up to | 8.3 |
| V | Siltstone, P-340, greenish gray; limy; satinspar in fractures | 18.3 |
| U | Limestone, P-338, 339, gray, dense; massive; stylolites; indeterminate fossils | 2.0 |

| | | |
|---|---|---|
| | Limestone, P-337, gray, silty; structureless | 1.2 |
| | (Unit "U" varies in thickness between 4 inches and 10 feet over short distances) | |
| $T_1$ | Siltstone, P-336, dark brown; slightly limy, gypsiferous | 3.5 |
| T | Siltstone, P-335, greenish gray; limy; laminated | 3.5 |
| S | Limestone, P-334, gray, crystalline, dense | 0.6 |
| | Limestone, P-333, gray, silty; laminated | 1.5 |
| | Disconformity: slight relief | |
| $Q_2$ | Siltstone, P-332, dark brown; gypsiferous throughout, especially near the top; gypsum layers up to 4 inches thick | 12.0 |
| P | Siltstone, P-331, greenish gray, alternating with limy siltstone; all ripple-marked; deformed by slumping | 5.8 |
| O | Siltstone, P-330, gray, limy, micaceous on bedding; with limy, hard siltstone thin layers, and nodules; thin-bedded and laminated | 20.6 |
| N | Limestone, P-329, 478, greenish gray; silty; ripple-marked; mud cracks in the middle of the layer; *Myalina*, *Bakewellia*, crinoid fragments, worm trails near the top | 1.5 |
| M | Siltstone, P-328, dark gray, limy, laminated | 1.6 |
| L | Limestone, P-326, 327, 477, gray crystalline; massive; silty near the top; crinoid fragments abundant, brachiopods abundant, *Aviculopecten* rare | 1.4 |
| | Disconformity | |
| I | Siltstone, P-302, 325, 476, gray and dark gray, limy; poorly preserved pelecypods abundant; cephalopods rare, *Tirolites spinosus* in the lowermost 6 feet | 21.8 |
| G | Limestone, P-323, 324, 475, gray; massive, irregular bedding; individual layers silty near the bottom, almost pure limestone near the top of the layers; crinoid fragments abundant; a few brachiopods; *Aviculopecten*, *Myalina*, *Bakewellia* common; gastropods rare; vermes incertae sedis; lower boundary of the unit covered by talus; exposed only | 5.5 |
| | Disconformity: here covered by talus | |
| F | Siltstone, P-321, 322, 298–302, 474, gray, limy, micaceous on bedding; irregular laminae; alternating with hard limy siltstone lenticular layers, and concretions; *Bakewellia*, small *Myalina* common in the lower part | 45.0 |
| D | Limestone, P-320, 473, gray, crystalline; silty near the top; crinoid fragments common; terebratulids and pelecypods rare to common | 3.0 |
| C | Limestone, P-319, 472, gray, crystalline; siltstone inclusions up to 1 inch in diameter near the base; stylolites; cross-stratification, upper surface bevelled; crinoid fragments abundant, other fossils indeterminate; the thickness varies from 1 foot 2 inches to | 3.1 |
| | Disconformity: pronounced relief | |
| B | Siltstone, P-317, 318, brown, limy; the uppermost 4 inches are gray and not calcareous; bedding irregular; top ripple-marked; up to | 2.6 |
| A | Limestone, P-316, 471, light gray, dense | 0.6 |
| | Limestone, P-470, gray, dense; oölitic; stylolites | 0.7 |
| | Limestone, P-469, light gray, silty; thin-bedded; poorly preserved pelecypods | 0.6 |
| | Limestone, P-315, gray, dense; lower surface uneven; 1 foot to | 1.3 |
| | Limestone, P-314, 468, gray; dense; ?biohermal | 1.6 |
| | Limestone, P-313, 467, gray; cross-stratified; lenses of silty limestone mark cross-bedding; mud cracks on top | 0.8 |
| | Limestone, P-312, 468, gray, dense; lenticular; fossils calcified; up to | 0.6 |
| | Limestone, P-465, gray, silty; partly eroded; lenticular; up to | 0.1 |
| | Limestone, P-311, 464, gray; "torrential" cross-bedding; thickness 2 inches to | 0.3 |
| | Limestone, P-310, gray; lenticular; brachiopods poorly preserved; up to | 0.2 |
| | Limestone, P-309, 463, gray, dense, massive; silty near the bottom | 1.2 |
| | Limestone, P-308, 462, gray, silty; laminated | 0.6 |
| | Limestone, P-461, gray, dense; lenticular; 1 inch to | 0.2 |
| | All the limestones of this unit ("A") overlie each other disconformably | |
| | Unconformity: considerable relief | |
| | Kaibab formation; lower part of the gypsiferous alpha member | |

*Section 13*

| | | |
|---|---|---|
| | Top of hill; recent erosion surface | |
| | Virgin formation: | |
| N | Limestone, P-414, gray, crystalline, porous; thick-bedded | 5.6 |
| | Disconformity: slight relief | |
| L | Limestone, P-413, gray, crystalline; | |

| | | |
|---|---|---|
| | structureless; small indeterminate fossils | 0.6 |
| | Limestone, yellow gray, silty; thin- and thick-bedded | 4.6 |
| | Limestone, P-412, gray, silty, crystalline | 0.3 |
| | Disconformity: here covered by talus | |
| I | Siltstone, P-411, gray, limy; thin-bedded and laminated; covered by talus; poorly preserved mollusks; "*Orthoceras*" in the lower 6 feet | 27.5 |
| G | Limestone, P-410, gray, dense; lenticular, irregular, thin layers; crinoid fragments; pelecypods, small gastropods; vermes | 6.3 |
| | Disconformity: here concealed | |
| F | Siltstone, P-409, gray, limy; poorly preserved pelecypods; slope covered by talus | 57.3 |
| D | Limestone, P-408, gray, dense; crinoid fragments; indeterminate pelecypods and brachiopods | 0.7 |
| C | Limestone, P-407, greenish gray, silty; thin, irregular bedding; with dense limestone thin layers; crinoid fragments, indeterminate pelecypods and brachiopods, replaced by calcite; exposed about | 1.6 |
| | The rest of the section covered by talus | |

*Section 14*

| | | |
|---|---|---|
| | Top of hill; recent erosion surface | |
| | Virgin formation | |
| X | Limestone, P-360, gray, crystalline; thin-bedded; crinoid fragments abundant | 4.0 |
| | Limestone, P-359, gray, silty; irregular bedding | 4.0 |
| | Contact covered; probably disconformity | |
| W | Siltstone, brown, gypsiferous; slope covered by talus | 44.6 |
| P | Siltstone, P-358, gray, limy; thin-bedded, ripple marks; deformed by slumping; raindrop imprints, trails of indeterminate animals | 1.6 |
| O | Siltstone, gray, limy; laminated | 1.6 |
| N | Limestone, P-357, gray crystalline; near the top silty and with green gray siltstone small inclusions | 2.4 |
| | Disconformity: no apparent relief | |
| I | Siltstone, P-355, 356, dark gray; limy; laminated; pelecypods; cephalopods in the lowermost 6 feet | 41.3 |
| G | Limestone, P-353, 354, greenish gray; massive; silty, especially near the top; crinoid fragments abundant, poorly preserved pelecypods abundant on the upper surface | 2.5 |
| | Disconformity: no apparent relief | |
| F | Siltstone, P-351, 352, gray, limy; irregular laminae; numerous hard limy siltstone thin lenses and concretions; *Bakewellia, Myalina* | 50.0 |
| D | Limestone, P-347–350, gray, crystalline; crinoid fragments abundant in the upper part; poorly preserved mollusks replaced by calcite, in the middle part | 4.6 |
| C | Limestone, P-345, 346, gray, crystalline; structureless; hard limestone concretions up to 2 feet in diameter in the uppermost part; crinoid fragments abundant, brachiopods rare | 5.8 |
| | Lower part of this limestone covered by talus. | |

*Section 15*

| | | |
|---|---|---|
| | Top of hill; recent erosion surface | |
| | Virgin formation: | |
| X | Limestone, P-392, gray, crystalline; thick-bedded; up to | 5.0 |
| | Limestone, P-391, gray, dense, crystalline; thick, irregular beds; indeterminate fossils replaced by calcite; up to | 10.8 |
| | Disconformity: no apparent relief | |
| W | Siltstone, brown, gypsiferous; slope covered by thick mantle of talus; the excessive thickness may be due to the repetition by thrust faulting which is likely to be present here | 78.0 |
| $P_1$ | Limestone, P-389, 390, greenish gray, very silty; ripple marks; crinoid fragments rare, pelecypods, *Aviculopecten* common | 2.0 |
| O | Siltstone, gray, limy; slope covered by talus | 5.6 |
| N | Limestone, P-386-388, greenish gray; crystalline; silty in the upper part; crinoid fragments abundant in crystalline limestone | 1.0 |
| | Disconformity: very slight relief | |
| I | Siltstone, P-384-385, gray, limy; micaceous on bedding; irregular ripple lamination; reddish brown and greenish gray near the top; ostracods | 41.6 |
| H | Limestone, P-383, olive gray, silty; fossils replaced by calcite | 0.8 |
| | Probably siltstone; slope covered by talus | 0.8 |
| G | Limestone, P-380-382, gray; crystalline; silty near the top; massive, ripple-marked in the upper part; crinoid fragments abundant in the crystalline lower part, common in the silty, upper part; pelecypods common | 4.2 |
| | Disconformity: no apparent relief | |
| F | Siltstone, P-378-379, gray, limy; lami- | |

| | | |
|---|---|---|
| | nated and locally ripple-marked; poorly preserved pelecypods | 39.3 |
| D | Limestone, P-374-377, light gray; porous; "torrential" cross-stratification; crinoid fragments very abundant; brachiopods common; contact with the underlying limestone of unit "C" marked by stylolites | 4.8 |
| C | Limestone, P-373, gray, silty; crinoid fragments common | 0.5 |
| | Limestone, P-371, 372, greenish gray; silty; thin- and thick-bedded; poorly preserved mollusks | 1.6 |
| | Disconformity: not apparent here | |
| B | Siltstone, brownish gray; slope covered by talus | 5.3 |
| A | Limestone, P-369, gray; massive, lenticular; alternating with silty, flaggy limestone | 3.3 |
| | Limestone, P-367-368, light gray and brown, silty; lenticular layers; fossiliferous | 1.2 |
| | Limestone, P-365, 366, gray, silty; thin-bedded, ripple-marked; locally cross-stratified; with limy siltstone irregular inclusions up to 2 inches in diameter | 1.5 |
| | Unconformity: moderate relief | |
| | Kaibab formation; alpha gypsiferous member | |

*Section 16*

| | | |
|---|---|---|
| | Top of hill; recent erosion surface | |
| | Virgin formation: | |
| X | Limestone, P-232, gray; massive; porous in the lower part; layers 4 inches to 2 feet thick; stylolites; indeterminate fossils replaced by calcite | 15.0 |
| | ?Disconformity: contact covered | |
| W | Siltstone, brown, gypsiferous; slope covered | 35.3 |
| $P_1$ | Siltstone, P-233, gray, limy; laminated and thin-bedded, ripple-marked; deformed by slumping; raindrop imprints, worm trails, and poorly preserved pelecypods | 2.3 |
| O | Siltstone, gray, limy; slope covered by talus | 7.0 |
| N | Limestone, P-231, gray, crystalline; massive; crinoid fragments abundant | 1.6 |
| | Disconformity: no relief visible | |
| I | Siltstone, brownish gray, limy; slope covered by talus | 22.0 |
| H | Limestone, gray, silty; massive | 1.6 |
| G | Limestone, P-230, gray, crystalline; massive; crinoid fragments abundant | 3.8 |
| | Limestone, P-229, gray; irregular, thin bedding | 3.0 |
| | Disconformity: slight relief | |
| F | Limestone, P-227, gray, crystalline; crinoid fragments abundant, brachiopods common, pelecypods common, to rare | 1.2 |
| C | Limestone, P-226, 228, gray crystalline; massive; cross-stratified; locally with limy siltstone small irregular inclusions | 2.0 |
| | Limestone, P-224, 225, gray; silty in the lower part, crystalline near the top | 1.8 |
| | Unconformity | |
| | Kaibab formation; alpha gypsiferous member | |

*Section 17*

| | | |
|---|---|---|
| | Top of hill; recent erosion surface | |
| | Virgin formation: | |
| X | Limestone, P-403–405, gray, dense; in layers 4 inches to 1 foot 10 inches thick; fossils replaced by calcite | 9.3 |
| | Disconformity: slight relief | |
| W | Siltstone, brown, strongly gypsiferous; silty gypsum thin and thick beds in the upper part | 55.0 |
| $P_1$ | Siltstone, P-402, greenish gray, limy; deformed by subaqueous slumping; ripple marks; raindrop imprints, worm trails, "shell and cast" structure | 2.6 |
| O | Siltstone, gray, limy; slope covered by talus | 6.2 |
| N | Limestone, P-401, gray, crystalline, silty; brachiopods very abundant | 0.8 |
| | Limestone, P-400, gray, crystalline; massive; crinoid fragments abundant, brachiopods rare | 2.0 |
| | Disconformity: no relief | |
| I | Siltstone, gray, limy; slope covered by talus | 41.6 |
| H | Limestone, gray, silty; thin-bedded | 1.5 |
| G | Limestone, P-399, gray, silty; irregular flaggy, and massive; crinoid fragments abundant | 4.3 |
| | Disconformity: no relief | |
| F | Siltstone, gray, limy; cross-ripple lamination common; slope covered by talus | 42.6 |
| D | Limestone, P-398, light gray, crystalline, massive | 4.2 |
| C | Limestone, P-396-397, gray, crystalline; massive; crinoid fragments abundant; hard limestone concretions 4 inches to 1 foot 8 inches in diameter, in the uppermost part | 5.2 |
| | Limestone, P-395, gray, coarse crystalline; massive | 0.8 |
| | Limestone, P-394, gray, fine crystalline; | |

massive; crinoid fragments abundant ..... 3.2

Unconformity: slight relief

Kaibab formation, alpha gypsiferous member

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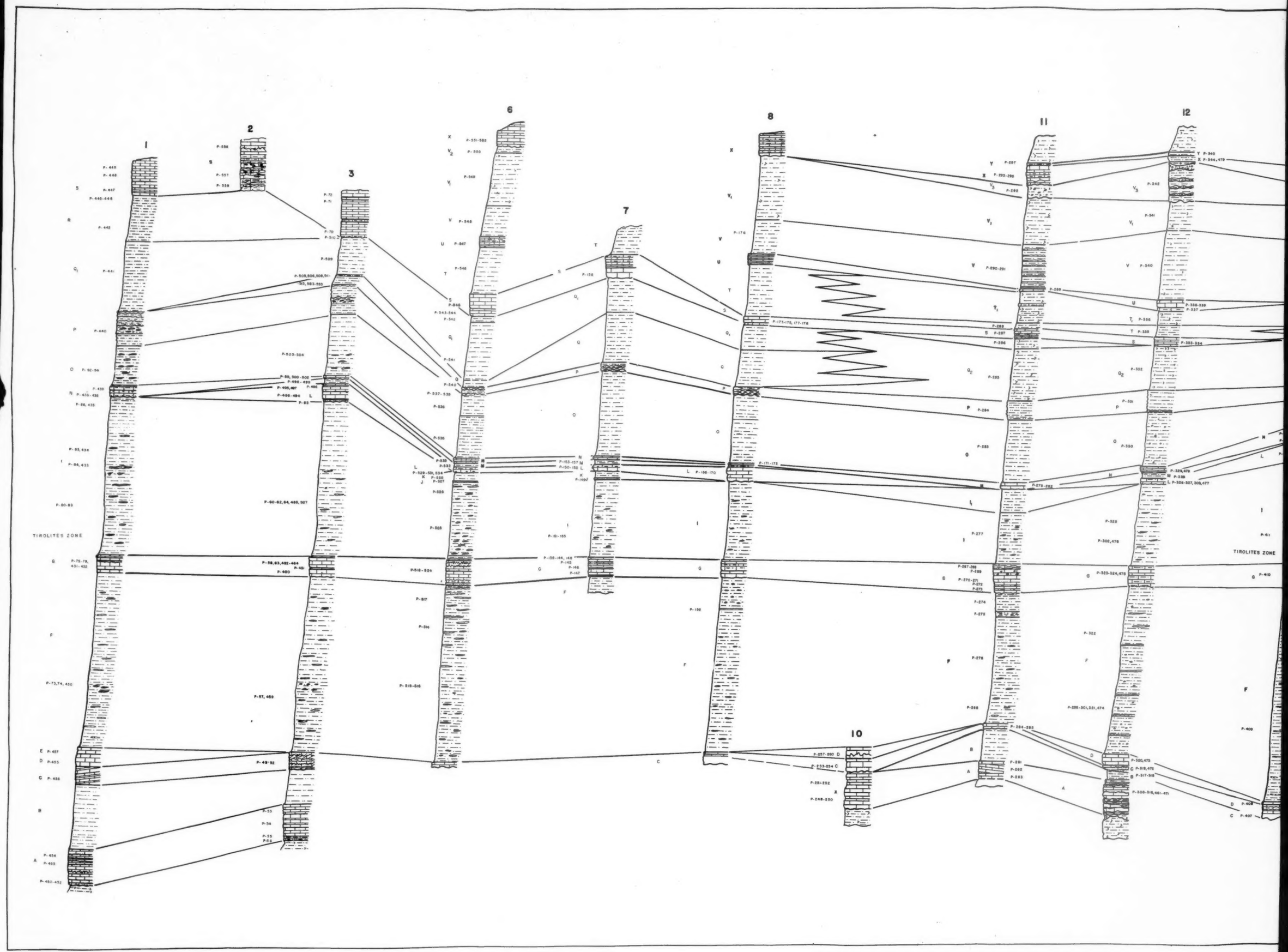
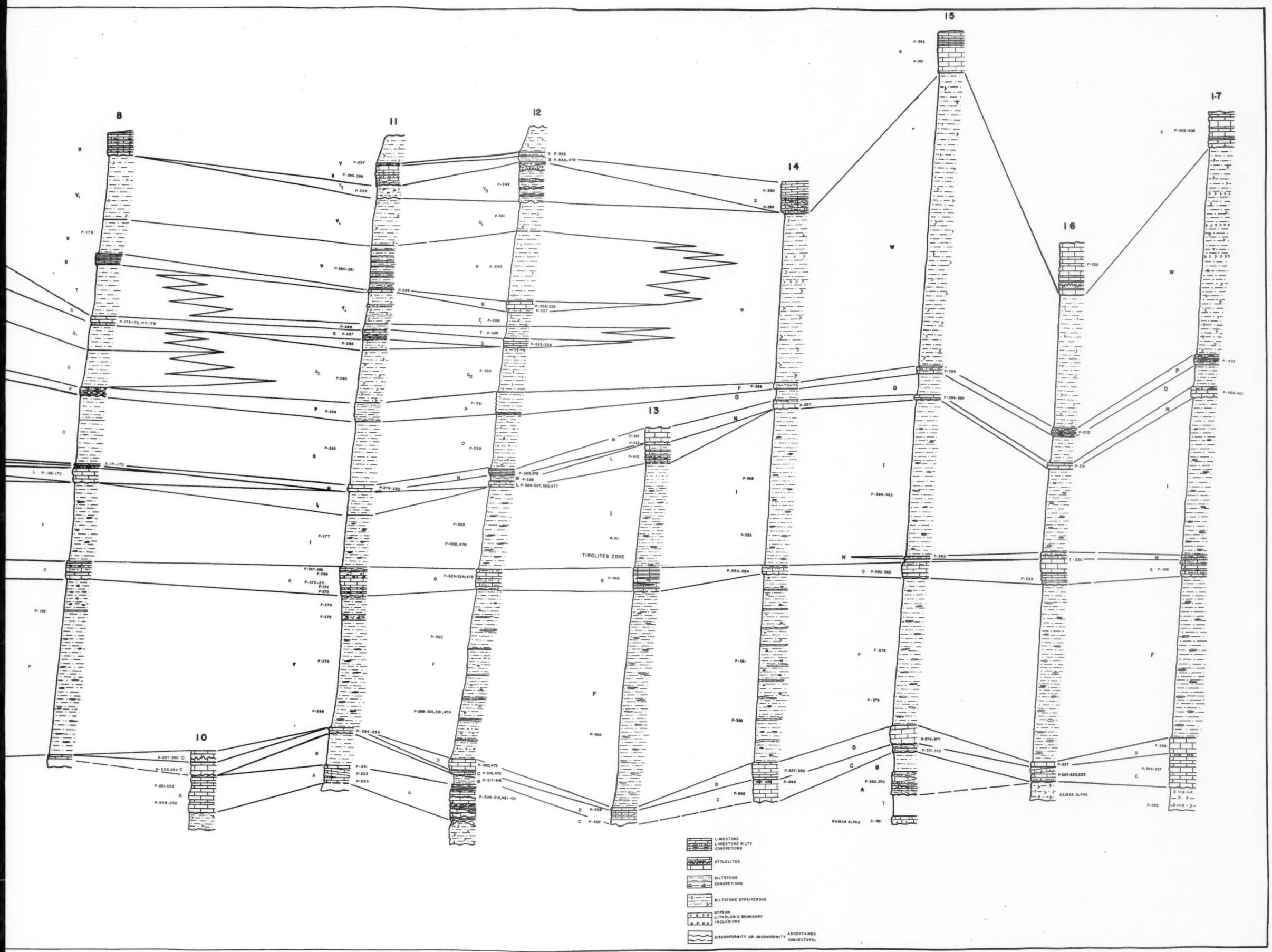
Manuscript Received by the Secretary of the Society, February 17, 1953.




SELECTED MEASURED SECTIONS OF THE VIRGIN FORMATION IN THE ST. GEORGE, UTAH, AREA

The units are designated by letters. Facies of single units are designated by subscript numbers following the letter by which the unit is designated. The sample numbers (*e.g.*, P-361) refer to a single layer or its part in the text.

Vertical scale, 1 inch = 20 feet

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 65, PP. 1007-1032 OCTOBER 1954

# AVERAGE CHEMICAL COMPOSITIONS OF SOME IGNEOUS ROCKS

BY S. R. NOCKOLDS

## ABSTRACT

Average chemical compositions are given for the common plutonic rock types and their volcanic equivalents. An attempt has been made also to give the general average chemical compositions of silicic, intermediate, subsilicic and ultramafic igneous rocks

## INTRODUCTION

The best-known average chemical compositions for various types of igneous rock are those computed by Prof. R. A. Daly. These were first published in 1910 (Daly, 1910), appeared with some improvements in 1914 (Daly, 1914 pp. 19–36), and with further improvements and some new averages in 1933 (Daly, 1933 pp. 9–28).

As many of the rock types have been more closely defined since Daly made his averages, and as some of the analyses he used were not up to modern standards, it seemed worth while to compute new averages. The analyses used were collected from the literature over a period of years, and care was taken to avoid including any but fresh rocks. This accounts for the relatively few analyses included in certain of the averages. It was found impossible to use many chemical analyses of fresh rocks either because there were insufficient modal data accompanying the analysis, or because such modal data were clearly at variance with the chemical analysis and its norm. Thus, the norm of the chemical analysis of a certain diopside granite showed more than 1 per cent of corundum. If the rock was fresh, and no mention was made of any alteration, then either the analysis was incorrect or diopside was not the only ferromagnesian constituent. In any case the analysis had to be discarded.

The classification followed for defining the rock types is, insofar as the plutonic representatives are concerned, a semi-quantitative mineralogical one.

Following Tröger and Shand, 10 per cent is taken as the upper limit for the quartz content of syenites and other intermediate igneous rocks, and the same value has been used to limit the feldspathoid content. When quartz or feldspathoid is visible in such rocks, the latter should be referred to as quartz-bearing or feldspathoid-bearing respectively.

The volcanic representatives of any given plutonic type are those which correspond in mineralogy and/or chemical composition. The hypabyssal representatives are, in general, not considered in the present paper.

CLASSIFICATION OF IGNEOUS ROCKS

| Other Essential Minerals | Essential Alkali-feldspar (Potash feldspar, or albite, or both) | Essential potash feldspar and lime-bearing plagioclase | | | | No essential feldspar (I.e. <10% of any feldspar present) |
|---|---|---|---|---|---|---|
| | | Potash feldspar >60% of total feldspar content | Potash feldspar between 60% and 40% of total feldspar content | Potash feldspar between 40% and 10% of total feldspar content | Potash feldspar <10% of total feldspar content | |
| *Quartz* > 10% of the rock | ALKALI GRANITE (alkali rhyolite)<br>PERALKALINE GRANITE (Peralkaline rhyolite) | CALC-ALKALI GRANITE (Calc-alkali rhyolite) | ADAMELLITE (Dellenite) | GRANODIORITE (Rhyodacite) | TONALITE (Dacite) | |
| No essential quartz or feldspathoid (I.e. < 10%) | ALKALI SYENITE (Alkali trachyte)<br>PERALKALINE SYENITE (Peralkaline trachyte) | CALC-ALKALI SYENITE (Calc-alkali trachyte) | MONZONITE (Latite) | MANGERITE (Doreite) | DIORITE (Andesite)<br>GABBRO (Basalt) | PERKNITE<br>PERIDOTITE |
| *Feldspathoid* > 10% of the rock | NEPHELINE SYENITE (Phonolite) | | NEPHELINE MONZONITE (Nepheline latite) | ESSEXITE (Nepheline ordanchite)<br>GLENMUIRITE (Analcite ordanchite) | THERALITE (Nepheline tephrite)<br>TESCHENITE (Analcite tephrite) | ULTRA-ALKALINE ROCKS (Nephelinite, etc.) |

Names of plutonic rocks are in capital letters, names of corresponding volcanic types in parentheses.

## Notes on Tables

The tables give the average chemical composition, and the norm of that average composition, for a number of the more common igneous rock types and rock groups:

TABLE 1: The term peralkaline is borrowed from Shand (Shand, 1950, p. 229) and used in the same sense.

TABLE 2: Contrary to the generally accepted opinion, lavas corresponding in composition to adamellite (the dellenites) and especially to granodiorite (the rhyodacites) are common. They have usually been described as "rhyolites" or "andesites".

TABLE 3: Insufficient analyses are available to give average compositions for any varieties of calc-alkali syenite. Among alkali syenites, however, there are sufficient analyses to give an average for ferrohastingsite syenite, and for aegirine syenite among the peralkaline syenites.

TABLE 4: The typical larvikite is now known to be an alkali monzonite and not a syenite.

TABLE 5: There are two main varieties of alkali mangerite. The first, here termed the "Aker type", has oligoclase as its lime-bearing plagioclase, and the typical dark mineral is aegirine or aegirine-augite. The second, here termed the "Hurum type", carries andesine or labradorite, and the typical dark mineral is a titaniferous augite. Volcanic equivalents of both types exist but have not been given special names. Average mugearite is very close in chemical composition to average alkali mangerite of Aker type and is only a special variety of alkali doreite.

TABLE 6: The distinction between diorite and gabbro is made on the nature of the plagioclase feldspar present, and not on that of the dark minerals or on the color index.

Certain lavas related to the tholeiitic basalts have feldspar whose average composition is andesine and not labradorite. These are averaged in column III under the heading tholeiitic andesite. This average differs markedly from that of the typical calc-alkali andesites given in column II.

Alkali diorites are known, but the number of analyzed rocks is insufficient to give a reliable average composition. On the other hand, a number of alkali andesites have been described and analyzed. Probably the best known are some of the so-called andesine andesites of the Hawaiian province.

TABLE 7: Pyroxene gabbro has both ortho- and clino-pyroxene as essential constituents.

The name norite is used here for a gabbroic rock in which orthopyroxene is the only essential pyroxene. Rocks, such as much of the "norite" of the Bushveld complex, which contain a good deal of clino- as well as orthopyroxene, are pyroxene gabbros and not true norites.

The alkali gabbros have titaniferous augite with or without femaghastingsite and olivine, and most of them are richer in apatite than normal gabbros. They may carry some accessory nepheline, but the normative nepheline in the norm of the average rock is due to the titaniferous augite and is not modal.

It is well known that the composition of anorthosite (here defined as containing $<10$ per cent of dark minerals) found as large massifs is very different from that found as localized bands, lenses, or small bodies associated with gabbroic or ultrabasic complexes. This contrast is well brought out by the average compositions of the two types (columns IV and V). Troctolite is used here for a gabbroic rock in which olivine is the only essential ferromagnesian constituent.

Although the typical tholeiitic basalt carries little or no olivine, a number of tholeiitic olivine basalts are known whose average composition is given in column VIII. The typical alkali basalt, on the other hand, has olivine as an essential constituent, but alkali basalts without olivine occur, and their average composition is given in column X. Again, certain alkali basalts are much enriched in olivine (column XI). The normative nepheline of the alkali basalts is due to the presence of titaniferous augite and as a rule is not expressed modally.

The basalts here termed "Central" Basalts are those found in association with the typical calc-alkali andesites, dacites, and rhyodacites at volcanic centers. They are mineralogically distinct from tholeiitic or alkali basalts and also chemically distinct, as may be seen by

comparing column XII with columns VII and IX.

TABLE 8: The alkali pyroxenites differ from the normal types by having titaniferous augite with or without subordinate magnesiohastingsite. Orthopyroxene is absent, and apatite is a characteristic accessory constituent.

TABLE 9: There are not sufficient analyses of alkali peridotites with fresh olivine to give a reliable average composition. These rocks show the same features as the alkali pyroxenites—namely, the presence of titaniferous augite with or without magnesiohastingsite and the characteristic accessory apatite.

TABLES 10 AND 10A: Two sets of averages are given for the nepheline syenites. In Table 10 averages are given for varieties based on the kind of feldspar present, irrespective of the dark minerals. The Juvet type has only potash feldspar. The Foya type has potash-soda feldspar, commonly microperthite, with or without subordinate albite. The Litchfield type has albite with subordinate potash feldspar, and the Mariupol type has albite alone.

In Table 10A the varieties are based on the ferromagnesian minerals present, irrespective of the type of feldspar.

TABLE 11: Glenmuirite and teschenite are mineralogically similar to essexite and theralite respectively, except that they carry analcite in place of nepheline. The term "tephrite" is usually used in a loose sense and would embrace the lavas which Lacroix named ordanchite. Here the name tephrite is restricted to the volcanic equivalents of theralites and teschenites.

TABLE 13: All the leucitic rocks have been placed together as they form a well-marked group. There appear to be no true plutonic representatives of the leucitic lavas. The coarse-grained leucitic rocks such as leucite monzonite, leucite gabbro, and missourite are what Washington would call subvolcanic. However, average olivine-melilite leucitite closely resembles average biotite pyroxenite except that the former has somewhat lower silica and higher potash.

TABLE 14: Average silicic igneous rock includes granites, adamellites, granodiorites, tonalites, and their volcanic equivalents. It has been suggested that thoroughly alkaline rocks such as nepheline syenites bulk too largely when averages are made because of the large number of analyses available of such rocks compared with their areal extent. Two averages are given, therefore, for intermediate igneous rock, one including analyses of nepheline syenite, nepheline monzonite, and their volcanic equivalents, and the other without these types. The remaining types included here are syenites, monzonites, mangerites, diorites, and their volcanic equivalents. In the same manner, two averages are given for subsilicic igneous rock. The first includes essexite, glenmuirite, theralite, teschenite, and their volcanic equivalents, in addition to gabbros, norites, anorthosites, troctolites, and basalts. The second excludes the nepheline (or analcite)-bearing types. Average ultramafic igneous rock includes the perknites, dunites, and peridotites.

The ultra-alkaline rocks and the leucitic rocks have not been used in the compilation of these general averages, as they are of negligible importance when considering igneous rocks as a whole.

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DEPARTMENT OF MINERALOGY AND PETROLOGY, CAMBRIDGE, ENGLAND

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TABLES 1–14

TABLE 1.—GRANITES AND RHYOLITES

| | CALC-ALKALI GRANITES AND RHYOLITE | | | | | | ALKALI GRANITES AND RHYOLITE | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1. | 2. | 3. | 4. | I. | II. | 5. | 6. | 7. | 8. | III. | IV. |
| $SiO_2$ | 71·59 | 73·28 | 70·56 | 71·31 | 72·08 | 73·66 | 73·84 | 74·63 | 75·01 | 70·46 | 73·86 | 74·57 |
| $TiO_2$ | 0·31 | 0·30 | 0·40 | 0·96 | 0·37 | 0·22 | 0·16 | 0·14 | 0·17 | 0·34 | 0·20 | 0·17 |
| $Al_2O_3$ | 14·69 | 13·33 | 14·00 | 12·67 | 13·86 | 13·45 | 14·29 | 13·86 | 13·16 | 14·37 | 13·75 | 12·58 |
| $Fe_2O_3$ | 0·56 | 0·87 | 0·91 | 0·91 | 0·86 | 1·25 | 0·34 | 0·52 | 0·94 | 1·09 | 0·78 | 1·30 |
| FeO | 1·56 | 1·38 | 2·41 | 3·53 | 1·67 | 0·75 | 0·75 | 0·89 | 0·88 | 2·48 | 1·13 | 1·02 |
| MnO | 0·07 | 0·05 | 0·06 | 0·02 | 0·06 | 0·03 | 0·05 | 0·04 | 0·07 | 0·05 | 0·05 | 0·05 |
| MgO | 0·54 | 0·50 | 0·48 | 0·37 | 0·52 | 0·32 | 0·21 | 0·33 | 0·24 | 0·22 | 0·26 | 0·11 |
| CaO | 1·28 | 1·17 | 1·63 | 1·74 | 1·33 | 1·13 | 0·69 | 0·57 | 0·56 | 1·19 | 0·72 | 0·61 |
| $Na_2O$ | 2·97 | 2·96 | 3·56 | 3·06 | 3·08 | 2·99 | 3·61 | 3·05 | 3·48 | 4·19 | 3·51 | 4·13 |
| $K_2O$ | 5·48 | 5·52 | 5·39 | 5·04 | 5·46 | 5·35 | 5·21 | 5·16 | 5·01 | 5·18 | 5·13 | 4·73 |
| $H_2O+$ | 0·69 | 0·50 | 0·50 | 0·33 | 0·53 | 0·78 | 0·60 | 0·63 | 0·37 | 0·37 | 0·47 | 0·66 |
| $P_2O_5$ | 0·26 | 0·14 | 0·10 | 0·06 | 0·18 | 0·07 | 0·25 | 0·18 | 0·11 | 0·06 | 0·14 | 0·07 |
| qz | 29·5 | 31·2 | 24·5 | 29·0 | 29·2 | 33·2 | 31·7 | 35·4 | 34·1 | 22·2 | 32·2 | 31·1 |
| or | 32·8 | 32·8 | 31·7 | 29·5 | 32·2 | 31·7 | 30·6 | 30·6 | 29·5 | 30·6 | 30·0 | 27·8 |
| ab | 25·2 | 25·2 | 29·9 | 25·7 | 26·2 | 25·1 | 30·4 | 25·7 | 29·3 | 35·6 | 29·3 | 35·1 |
| an | 4·5 | 5·0 | 6·4 | 6·4 | 5·6 | 5·0 | 1·7 | 1·9 | 2·2 | 5·0 | 2·8 | 2·0 |
| C | 2·1 | 0·5 | — | — | 0·8 | 0·9 | 2·1 | 2·5 | 1·3 | — | 1·4 | — |
| $CaSiO_3$ | — | — | 0·3 | 0·7 | — | — | — | — | — | 0·1 | — | 0·1 |
| $MgSiO_3$ | 1·3 | 1·3 | 1·2 | 0·9 | 1·3 | 0·8 | 0·5 | 0·8 | 0·6 | 0·5 | 0·6 | 0·3 |
| $FeSiO_3$ | 1·9 | 1·3 | 3·0 | 4·1 | 1·7 | — | 0·9 | 1·1 | 0·7 | 3·1 | 1·1 | 0·6 |
| ac | — | — | — | — | — | — | — | — | — | — | — | — |
| mt | 0·9 | 1·2 | 1·4 | 1·4 | 1·4 | 1·9 | 0·5 | 0·7 | 1·4 | 1·6 | 1·2 | 1·9 |
| il | 0·6 | 0·6 | 0·8 | 1·8 | 0·8 | 0·5 | 0·3 | 0·3 | 0·3 | 0·6 | 0·5 | 0·3 |
| hm | — | — | — | — | — | — | — | — | — | — | — | — |
| ap | 0·7 | 0·3 | 0·3 | 0·2 | 0·4 | 0·2 | 0·6 | 0·4 | 0·3 | 0·2 | 0·3 | 0·2 |
| No. of analyses | (21) | (37) | (6) | (4) | (72) | (22) | (6) | (17) | (12) | (8) | (48) | (21) |

* Also 0·6 of Na-metasilicate

1. Muscovite-biotite granite
2. Biotite granite
3. Biotite-hornblende granite
4. Hypersthene-bearing granite
I. Average calc-alkali granite
II. Average calc-alkali rhyolite + rhyolite-obsidian
5. Muscovite granite
6. Muscovite-biotite alkali granite
7. Biotite alkali granite
8. Ferrohastingsite granite
III. Average alkali granite
IV. Average alkali rhyolite + rhyolite-obsidian

TABLE 1.—*Continued*

| PERALKALINE GRANITES AND RHYOLITE | | | | | | | |
|---|---|---|---|---|---|---|---|
| 9. | 10. | 11. | 12. | 13. | V. | VI. | |
| 73·05 | 71·66 | 70·68 | 71·47 | 67·29 | 71·08 | 72·31 | $SiO_2$ |
| 0·24 | 0·36 | 0·41 | 0·39 | 0·68 | 0·40 | 0·42 | $TiO_2$ |
| 10·62 | 9·73 | 10·90 | 13·91 | 12·26 | 11·26 | 10·88 | $Al_2O_3$ |
| 3·04 | 5·34 | 6·06 | 1·91 | 4·25 | 4·28 | 2·92 | $Fe_2O_3$ |
| 2·98 | 2·75 | 0·90 | 1·28 | 3·03 | 2·19 | 2·42 | FeO |
| 0·21 | 0·12 | 0·07 | 0·12 | 0·08 | 0·11 | 0·14 | MnO |
| 0·10 | 0·32 | 0·22 | 0·32 | 0·33 | 0·25 | 0·16 | MgO |
| 0·60 | 0·66 | 0·92 | 0·64 | 1·62 | 0·84 | 0·68 | CaO |
| 4·23 | 4·45 | 5·36 | 5·63 | 5·42 | 4·92 | 5·17 | $Na_2O$ |
| 4·48 | 4·12 | 4·13 | 3·93 | 4·46 | 4·21 | 4·42 | $K_2O$ |
| 0·37 | 0·42 | 0·29 | 0·34 | 0·48 | 0·39 | 0·45 | $H_2O+$ |
| 0·08 | 0·07 | 0·06 | 0·06 | 0·10 | 0·07 | 0·03 | $P_2O_5$ |
| 29·9 | 30·0 | 25·5 | 22·2 | 17·0 | 26·2 | 26·4 | qz |
| 26·7 | 24·5 | 24·5 | 23·4 | 26·7 | 25·0 | 26·1 | or |
| 29·3 | 26·7 | 33·0 | 47·7 | 38·2 | 34·6 | 31·4 | ab |
| — | — | — | 0·8 | — | — | — | an |
| — | — | — | — | — | — | — | c |
| 1·0 | 1·2 | 1·6 | 0·6 | 3·0 | 1·4 | 1·4 | $CaSiO_3$ |
| 0·3 | 0·8 | 0·5 | 0·3 | 0·8 | 0·6 | 0·4 | $MgSiO_3$ |
| 4·6 | 2·9 | — | 2·9 | 2·8 | 1·7 | 4·0 | $FeSiO_3$ |
| 5·5 | 9·7 | 10·6 | — | 6·4 | 6·0 | 8·3 | ac |
| 1·6 | 2·8 | 2·1 | 2·8 | 3·0 | 3·2 | — | mt |
| 0·5 | 0·8 | 0·8 | 0·8 | 1·4 | 0·8 | 0·8 | il |
| — | — | 1·0 | — | — | — | — | hm |
| 0·2 | 0·2 | 0·2 | 0·2 | 0·3 | 0·2 | 0·1 * | ap |
| (10) | (14) | (11) | (9) | (8) | (53) | (39) | No. of analyses |

RIEBECKITE (OR OSANNITE) GRANITE

RIEBECKITE–AEGIRINE GRANITE

AEGIRINE GRANITE

ARFVEDSONITE–AEGIRINE GRANITE

LANEITE–AEGIRINE GRANITE

AVERAGE PERALKALINE GRANITE

AVERAGE PERALKALINE RHYOLITE–OBSIDIAN

TABLE 2.—ADAMELLITES AND DELLENITE, GRANODIORITES AND RHYODACITE, TONALITES AND DACITE

| | ADAMELLITES AND DELLENITE | | | | | | GRANODIORITES AND RHYODACITE | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1. | 2. | 3. | 4. | I. | II. | 5. | 6. | 7. | 8. | III. | IV. |
| $SiO_2$ | 71·86 | 71·03 | 65·88 | 68·91 | 69·15 | 70·15 | 70·47 | 68·97 | 65·50 | 62·64 | 66·88 | 66·27 |
| $TiO_2$ | 0·30 | 0·39 | 0·81 | 0·76 | 0·56 | 0·42 | 0·30 | 0·45 | 0·61 | 1·32 | 0·57 | 0·66 |
| $Al_2O_3$ | 14·73 | 14·31 | 15·07 | 13·93 | 14·63 | 14·41 | 15·50 | 15·47 | 15·65 | 15·82 | 15·66 | 15·39 |
| $Fe_2O_3$ | 0·64 | 0·95 | 1·74 | 1·48 | 1·22 | 1·68 | 0·63 | 1·12 | 1·63 | 1·59 | 1·33 | 2·14 |
| FeO | 1·61 | 1·96 | 2·73 | 3·20 | 2·27 | 1·55 | 2·12 | 2·05 | 2·79 | 4·31 | 2·59 | 2·23 |
| MnO | 0·04 | 0·06 | 0·08 | 0·04 | 0·06 | 0·06 | 0·03 | 0·06 | 0·09 | 0·09 | 0·07 | 0·07 |
| MgO | 0·67 | 0·75 | 1·38 | 1·02 | 0·99 | 0·63 | 0·65 | 1·15 | 1·86 | 2·83 | 1·57 | 1·57 |
| CaO | 1·51 | 1·89 | 3·36 | 3·06 | 2·45 | 2·15 | 1·91 | 2·99 | 4·10 | 4·72 | 3·56 | 3·68 |
| $Na_2O$ | 3·18 | 3·33 | 3·53 | 3·00 | 3·35 | 3·65 | 4·12 | 3·69 | 3·84 | 3·37 | 3·84 | 4·13 |
| $K_2O$ | 4·64 | 4·66 | 4·64 | 4·10 | 4·58 | 4·50 | 3·59 | 3·16 | 3·01 | 2·62 | 3·07 | 3·01 |
| $H_2O+$ | 0·66 | 0·50 | 0·52 | 0·38 | 0·54 | 0·68 | 0·52 | 0·70 | 0·69 | 0·42 | 0·65 | 0·68 |
| $P_2O_5$ | 0·16 | 0·17 | 0·26 | 0·12 | 0·20 | 0·12 | 0·16 | 0·19 | 0·23 | 0·27 | 0·21 | 0·17 |
| qz | 30·7 | 27·7 | 18·8 | 27·0 | 24·8 | 26·1 | 27·1 | 26·2 | 20·0 | 17·7 | 21·9 | 20·8 |
| or | 27·2 | 27·8 | 27·2 | 24·5 | 27·2 | 26·7 | 21·1 | 18·9 | 17·8 | 15·6 | 18·3 | 17·8 |
| ab | 27·3 | 28·3 | 29·9 | 25·2 | 28·3 | 30·9 | 34·6 | 31·4 | 32·5 | 28·3 | 32·5 | 35·1 |
| an | 6·7 | 8·6 | 11·7 | 12·2 | 11·1 | 9·5 | 8·6 | 14·2 | 16·4 | 20·3 | 16·4 | 14·5 |
| C | 1·9 | 0·5 | — | — | — | — | 1·7 | 0·7 | — | — | — | — |
| $CaSiO_3$ | — | — | 1·4 | 0·9 | — | 0·2 | — | — | 0·9 | 0·6 | — | 1·3 |
| $MgSiO_3$ | 1·7 | 1·9 | 3·4 | 2·5 | 2·5 | 1·6 | 1·6 | 2·9 | 4·6 | 7·1 | 3·9 | 3·9 |
| $FeSiO_3$ | 2·0 | 2·2 | 2·4 | 3·3 | 2·2 | 0·8 | 2·8 | 2·2 | 2·9 | 4·7 | 2·9 | 1·3 |
| mt | 0·9 | 1·4 | 2·6 | 2·1 | 1·9 | 2·5 | 0·9 | 1·6 | 2·3 | 2·3 | 1·9 | 3·0 |
| il | 0·6 | 0·8 | 1·5 | 1·5 | 1·1 | 0·6 | 0·6 | 0·8 | 1·2 | 2·4 | 1·1 | 1·4 |
| ap | 0·3 | 0·3 | 0·6 | 0·3 | 0·5 | 0·3 | 0·3 | 0·4 | 0·6 | 0·7 | 0·5 | 0·3 |
| No. of analyses | (22) | (45) | (41) | (11) | (121) | (58) | (20) | (36) | (65) | (10) | (137) | (115) |

1. Muscovite-biotite adamellite
2. Biotite adamellite
3. Hornblende-biotite adamellite
4. Hypersthene-bearing adamellite
I. Average adamellite
II. Average dellenite + dellenite-obsidian
5. Muscovite-biotite granodiorite
6. Biotite granodiorite
7. Hornblende-biotite granodiorite
8. Hypersthene-bearing granodiorite
III. Average granodiorite
IV. Average rhyodacite + rhyodacite-obsidian

TABLE 2.—*Continued*

| TONALITES AND DACITE | | | | | | |
|---|---|---|---|---|---|---|
| 9. | 10. | 11. | 12. | V. | VI. | |
| 70·63 | 69·35 | 64·41 | 63·92 | 66·15 | 63·58 | $SiO_2$ |
| 0·37 | 0·48 | 0·62 | 1·03 | 0·62 | 0·64 | $TiO_2$ |
| 15·69 | 14·93 | 15·95 | 15·60 | 15·56 | 16·67 | $Al_2O_3$ |
| 0·86 | 1·19 | 1·46 | 1·70 | 1·36 | 2·24 | $Fe_2O_3$ |
| 1·40 | 3·07 | 3·81 | 4·61 | 3·42 | 3·00 | FeO |
| 0·04 | 0·06 | 0·10 | 0·07 | 0·08 | 0·11 | MnO |
| 0·83 | 0·94 | 2·45 | 2·54 | 1·94 | 2·12 | MgO |
| 2·82 | 3·04 | 5·36 | 5·23 | 4·65 | 5·53 | CaO |
| 4·91 | 4·67 | 3·39 | 3·54 | 3·90 | 3·98 | $Na_2O$ |
| 1·68 | 1·48 | 1·45 | 1·22 | 1·42 | 1·40 | $K_2O$ |
| 0·62 | 0·64 | 0·80 | 0·33 | 0·69 | 0·56 | $H_2O+$ |
| 0·15 | 0·15 | 0·20 | 0·21 | 0·21 | 0·17 | $P_2O_5$ |
| 28·3 | 27·4 | 22·7 | 22·1 | 24·1 | 19·6 | q |
| 10·0 | 8·9 | 8·3 | 7·2 | 8·3 | 8·3 | or |
| 41·4 | 39·3 | 28·8 | 29·9 | 33·0 | 34·1 | ab |
| 13·1 | 14·2 | 23·9 | 23·1 | 20·8 | 23·3 | an |
| 1·0 | 0·4 | — | — | — | — | C |
| — | — | 0·6 | 0·7 | 0·3 | 1·3 | $CaSiO_3$ |
| 2·1 | 2·3 | 6·1 | 6·3 | 4·9 | 5·3 | $MgSiO_3$ |
| 1·1 | 3·8 | 4·9 | 5·4 | 4·1 | 2·8 | $FeSiO_3$ |
| 1·4 | 1·9 | 2·1 | 2·5 | 2·1 | 3·3 | mt |
| 0·8 | 0·9 | 1·2 | 2·0 | 1·2 | 1·2 | il |
| 0·3 | 0·3 | 0·5 | 0·5 | 0·5 | 0·3 | ap |
| (9) | (11) | (22) | (10) | (58) | (50) | No. of analyses |

9. Muscovite-biotite tonalite
10. Biotite tonalite
11. Hornblende-biotite tonalite
12. Hypersthene-bearing tonalite
V. Average tonalite
VI. Average dacite + dacite-obsidian

TABLE 3.—SYENITES AND TRACHYTES

| | CALC-ALKALI SYENITE AND TRACHYTE | | | ALKALI SYENITES AND TRACHYTES | | | | | | PERALKALINE SYENITE AND TRACHYTE | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | I. | II. | III. | 1. | IV. | V. | 2. | 3. | 4. | 5. | VI. | VII. |
| $SiO_2$ | 59.41 | 52.16 | 58.31 | 61.54 | 61.86 | 61.95 | 50.16 | 49.79 | 50.26 | 63.75 | 61.65 | 61.65 |
| $TiO_2$ | 0.83 | 1.61 | 0.66 | 0.59 | 0.58 | 0.73 | 1.20 | 0.84 | 1.22 | 0.66 | 0.52 | 0.52 |
| $Al_2O_3$ | 17.12 | 12.82 | 18.05 | 17.45 | 16.91 | 18.03 | 13.20 | 11.06 | 13.29 | 15.32 | 14.73 | 17.22 |
| $Fe_2O_3$ | 2.19 | 2.63 | 2.54 | 1.82 | 2.32 | 2.33 | 4.24 | 3.36 | 3.27 | 4.11 | 4.56 | 3.16 |
| FeO | 2.83 | 6.90 | 2.02 | 3.10 | 2.63 | 1.51 | 5.25 | 5.72 | 4.63 | 1.53 | 3.68 | 1.81 |
| MnO | 0.08 | 0.19 | 0.14 | 0.09 | 0.11 | 0.13 | 0.33 | 0.13 | 0.10 | 0.17 | 0.20 | 0.19 |
| MgO | 2.02 | 7.20 | 2.07 | 0.74 | 0.96 | 0.63 | 7.15 | 9.78 | 7.98 | 0.36 | 0.70 | 0.45 |
| CaO | 4.06 | 8.21 | 4.25 | 2.39 | 2.54 | 1.89 | 8.67 | 9.61 | 9.30 | 1.52 | 1.87 | 1.58 |
| $Na_2O$ | 3.92 | 2.61 | 3.85 | 5.59 | 5.46 | 6.55 | 2.92 | 2.18 | 2.19 | 7.28 | 6.69 | 6.92 |
| $K_2O$ | 6.53 | 4.39 | 7.38 | 5.97 | 5.91 | 5.53 | 5.37 | 5.23 | 5.27 | 4.62 | 4.65 | 5.80 |
| $H_2O+$ | 0.63 | 0.58 | 0.53 | 0.59 | 0.53 | 0.54 | 0.75 | 1.34 | 1.81 | 0.53 | 0.58 | 0.58 |
| $P_2O_5$ | 0.38 | 0.70 | 0.20 | 0.19 | 0.19 | 0.18 | 0.76 | 0.96 | 0.68 | 0.15 | 0.17 | 0.12 |
| qz | 2.0 | — | — | 0.1 | 1.7 | — | — | — | — | 3.3 | 1.6 | — |
| or | 38.4 | 26.1 | 43.9 | 35.6 | 35.0 | 32.8 | 31.7 | 30.6 | 31.1 | 27.2 | 27.8 | 34.5 |
| ab | 33.0 | 22.0 | 28.8 | 47.2 | 46.1 | 54.0 | 9.4 | 6.8 | 10.0 | 52.9 | 49.2 | 50.3 |
| an | 10.0 | 10.0 | 9.7 | 4.7 | 4.2 | 3.3 | 7.0 | 5.3 | 10.8 | — | — | — |
| ne | — | — | 2.0 | — | — | 0.6 | 8.2 | 6.3 | 4.5 | — | — | 3.1 |
| ac | — | — | — | — | — | — | — | — | — | 7.8 | 6.5 | 1.9 |
| $CaSiO_3$ | 3.0 | 10.8 | 4.2 | 2.7 | 3.0 | 2.1 | 13.1 | 15.0 | 12.8 | 2.7 | 3.5 | 3.0 |
| $MgSiO_3$ | 5.0 | 6.9 | 3.2 | 1.8 | 2.4 | 1.6 | 9.4 | 10.7 | 9.6 | 0.9 | 1.7 | 1.1 |
| $FeSiO_3$ | 2.1 | 3.2 | 0.6 | 3.3 | 2.1 | — | 2.5 | 2.9 | 1.8 | 0.8 | 4.4 | 0.8 |
| $Mg_2SiO_4$ | — | 7.7 | 1.4 | — | — | — | 5.9 | 9.5 | 7.2 | — | — | — |
| $Fe_2SiO_4$ | — | 4.1 | 0.2 | — | — | — | 1.8 | 2.9 | 1.5 | — | — | — |
| mt | 3.3 | 3.7 | 3.7 | 2.5 | 3.3 | 3.3 | 6.0 | 4.9 | 4.9 | 2.1 | 3.5 | 3.7 |
| il | 1.5 | 3.0 | 1.2 | 1.2 | 1.2 | 1.4 | 2.3 | 1.5 | 2.3 | 1.2 | 0.9 | 0.9 |
| ap | 1.0 | 1.7 | 0.5 | 0.5 | 0.5 | 0.4 | 1.8 | 2.3 | 1.7 | 0.3 | 0.4 | 0.3 |
| No. of analyses | (18) | (6) | (24) | (11) | (25) | (15) | (8) | (9) | (6) | (13) | (47) | (12) |

I. AVERAGE CALC-ALKALI SYENITE (LEUCOCRATIC)
II. AVERAGE CALC-ALKALI SYENITE (MESOTYPE TO MELANOCRATIC)
III. AVERAGE CALC-ALKALI TRACHYTE
1. FERRO HASTINGSITE SYENITE
IV. AVERAGE ALKALI SYENITE
V. AVERAGE ALKALI TRACHYTE
2. AUGITE-BIOTITE SHONKINITE
3. AUGITE-BIOTITE-OLIVINE SHONKINITE
4. ALKALI TRACHYTE LAVAS CORRESPONDING WITH SHONKINITE
5. AEGIRINE SYENITE
VI. AVERAGE PERALKALINE SYENITE
VII. AVERAGE PERALKALINE TRACHYTE

TABLE 4.—MONZONITES AND LATITE

| | 1. | 2. | 3. | 4. | I. | II. | 5. |
|---|---|---|---|---|---|---|---|
| $SiO_2$ | 58·45 | 53·39 | 51·74 | 54·58 | 55·36 | 54·02 | 57·01 |
| $TiO_2$ | 1·40 | 1·07 | 1·14 | 0·84 | 1·12 | 1·18 | 1·67 |
| $Al_2O_3$ | 15·65 | 16·11 | 14·76 | 16·83 | 16·58 | 17·22 | 17·88 |
| $Fe_2O_3$ | 3·34 | 2·74 | 1·86 | 3·02 | 2·57 | 3·83 | 2·30 |
| FeO | 3·99 | 4·64 | 6·96 | 4·71 | 4·58 | 3·98 | 4·18 |
| MnO | 0·09 | 0·11 | 0·19 | 0·13 | 0·13 | 0·12 | 0·14 |
| MgO | 2·51 | 4·84 | 7·33 | 3·72 | 3·67 | 3·87 | 1·54 |
| CaO | 5·55 | 7·68 | 8·42 | 6·62 | 6·76 | 6·76 | 4·39 |
| $Na_2O$ | 3·47 | 3·44 | 2·68 | 3·52 | 3·51 | 3·32 | 5·80 |
| $K_2O$ | 4·61 | 4·75 | 3·93 | 4·79 | 4·68 | 4·43 | 4·03 |
| $H_2O+$ | 0·43 | 0·73 | 0·52 | 0·82 | 0·60 | 0·78 | 0·43 |
| $P_2O_5$ | 0·51 | 0·50 | 0·47 | 0·42 | 0·44 | 0·49 | 0·63 |
| qz | 7·7 | — | — | — | — | 0·5 | — |
| or | 27·2 | 27·8 | 23·3 | 28·4 | 27·8 | 26·1 | 23·9 |
| ab | 29·3 | 24·6 | 20·4 | 29·3 | 29·3 | 27·8 | 46·6 |
| an | 13·3 | 14·7 | 16·4 | 16·1 | 15·8 | 19·2 | 10·6 |
| ne | — | 2·3 | 1·4 | — | — | — | 1·4 |
| $CaSiO_3$ | 4·5 | 8·5 | 9·3 | 5·8 | 6·3 | 4·5 | 3·0 |
| $MgSiO_3$ | 6·3 | 5·7 | 5·7 | 5·1 | 8·0 | 9·7 | 1·6 |
| $FeSiO_3$ | 2·4 | 2·1 | 3·0 | 2·9 | 4·1 | 2·4 | 1·3 |
| $Mg_2SiO_4$ | — | 4·5 | 8·8 | 2·9 | 0·8 | — | 1·5 |
| $Fe_2SiO_4$ | — | 1·8 | 5·1 | 1·6 | 0·4 | — | 1·4 |
| mt | 4·9 | 3·9 | 2·8 | 4·4 | 3·7 | 5·6 | 3·3 |
| il | 2·7 | 2·1 | 2·1 | 1·5 | 2·1 | 2·3 | 3·2 |
| ap | 1·2 | 1·2 | 1·1 | 1·0 | 1·0 | 1·2 | 1·5 |
| No. of analyses | (5) | (11) | (6) | (9) | (46) | (42) | (15) |
| | Hornblende-biotite monzonite | Augite-biotite monzonite | Augite-biotite-olivine monzonite | Pyroxene-hornblende-biotite monzonite | Average monzonite | Average latite | Larvikite |

TABLE 5.—MANGERITES AND DOREITES

| | MANGERITES AND DOREITE (CALC-ALKALI) | | | | | | MANGERITES AND DOREITES (ALKALI) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1. | 2. | 3. | 4. | I. | II. | 5. | 6. | 7. | 8. | 9. | III. | IV. |
| $SiO_2$ | 55·86 | 55·83 | 55·06 | 54·18 | 54·66 | 56·00 | 56·75 | 46·82 | 55·12 | 54·28 | 48·09 | 50·00 | 51·32 |
| $TiO_2$ | 1·09 | 0·83 | 1·30 | 1·24 | 1·09 | 1·29 | 1·44 | 2·70 | 1·55 | 1·89 | 2·87 | 2·29 | 2·29 |
| $Al_2O_3$ | 17·22 | 16·51 | 16·71 | 17·94 | 16·98 | 16·81 | 17·72 | 15·64 | 17·78 | 16·57 | 15·91 | 16·31 | 16·64 |
| $Fe_2O_3$ | 2·92 | 3·09 | 3·40 | 3·09 | 3·26 | 3·74 | 2·79 | 4·57 | 3·11 | 2·95 | 3·39 | 3·99 | 3·24 |
| FeO | 5·01 | 5·88 | 5·48 | 4·66 | 5·38 | 4·36 | 4·46 | 7·10 | 4·98 | 6·74 | 7·40 | 6·26 | 6·48 |
| MnO | 0·13 | 0·14 | 0·12 | 0·14 | 0·14 | 0·13 | 0·20 | 0·20 | 0·14 | 0·17 | 0·18 | 0·20 | 0·16 |
| MgO | 3·42 | 3·35 | 4·02 | 3·48 | 3·95 | 3·39 | 1·96 | 5·64 | 2·18 | 2·45 | 6·15 | 4·46 | 4·30 |
| CaO | 6·75 | 6·44 | 6·79 | 7·13 | 6·99 | 6·87 | 5·24 | 9·77 | 5·47 | 5·05 | 8·80 | 8·33 | 7·47 |
| $Na_2O$ | 3·57 | 4·12 | 3·46 | 3·95 | 3·76 | 3·56 | 5·20 | 3·62 | 5·70 | 5·68 | 3·95 | 4·27 | 4·78 |
| $K_2O$ | 2·82 | 3·00 | 2·72 | 3·24 | 2·76 | 2·60 | 3·13 | 2·11 | 2·78 | 2·76 | 1·93 | 2·43 | 2·33 |
| $H_2O+$ | 0·79 | 0·56 | 0·51 | 0·54 | 0·60 | 0·92 | 0·61 | 0·94 | 0·58 | 0·68 | 0·66 | 0·83 | 0·63 |
| $P_2O_5$ | 0·42 | 0·25 | 0·43 | 0·41 | 0·43 | 0·33 | 0·50 | 0·69 | 0·61 | 0·78 | 0·67 | 0·63 | 0·66 |
| qz | 5·6 | 1·9 | 4·7 | 0·1 | 2·0 | 7·2 | 1·6 | — | — | — | — | — | — |
| or | 16·7 | 17·8 | 16·1 | 18·9 | 16·7 | 15·6 | 18·3 | 12·2 | 16·7 | 16·7 | 11·1 | 14·4 | 13·9 |
| ab | 29·9 | 34·6 | 29·3 | 33·5 | 31·9 | 29·9 | 44·0 | 22·0 | 47·2 | 47·2 | 27·2 | 29·9 | 35·1 |
| an | 22·8 | 17·8 | 22·0 | 21·4 | 21·1 | 22·2 | 15·9 | 19·5 | 14·7 | 11·7 | 20·0 | 18·1 | 17·0 |
| ne | — | — | — | — | — | — | — | 5·4 | 0·6 | 0·3 | 3·4 | 3·4 | 2·8 |
| $CaSiO_3$ | 3·2 | 5·1 | 3·7 | 4·8 | 4·5 | 4·1 | 2·9 | 10·1 | 3·6 | 3·2 | 7·9 | 8·2 | 6·2 |
| $MgSiO_3$ | 8·5 | 8·4 | 10·0 | 8·7 | 9·9 | 8·5 | 4·9 | 6·8 | 1·9 | 1·5 | 5·2 | 5·3 | 3·8 |
| $FeSiO_3$ | 5·2 | 7·2 | 5·3 | 4·3 | 5·4 | 3·0 | 3·8 | 2·5 | 1·6 | 1·7 | 2·1 | 2·4 | 2·0 |
| $Mg_2SiO_4$ | — | — | — | — | — | — | — | 5·0 | 2·4 | 3·2 | 7·1 | 4·0 | 4·9 |
| $Fe_2SiO_4$ | — | — | — | — | — | — | — | 2·0 | 2·0 | 3·9 | 3·3 | 1·8 | 2·9 |
| mt | 4·2 | 4·4 | 4·9 | 4·4 | 4·9 | 5·3 | 4·2 | 6·7 | 4·4 | 4·4 | 4·9 | 5·8 | 4·6 |
| il | 2·1 | 1·5 | 2·4 | 2·3 | 2·1 | 2·4 | 2·7 | 5·2 | 2·9 | 3·6 | 5·5 | 4·4 | 4·4 |
| ap | 1·0 | 0·7 | 1·0 | 1·0 | 1·0 | 0·8 | 1·2 | 1·7 | 1·4 | 1·9 | 1·6 | 1·5 | 1·6 |
| No. of analyses | (9) | (10) | (11) | (7) | (56) | (38) | (17) | (36) | (26) | (10) | (40) | (53) | (76) |

1. HORNBLENDE-BIOTITE MANGERITE
2. PYROXENE-HORNBLENDE-BIOTITE MANGERITE
3. PYROXENE-BIOTITE MANGERITE
4. AUGITE-BIOTITE MANGERITE
I. AVERAGE MANGERITE
II. AVERAGE DOREITE
5. ALKALI MANGERITE OF AKER TYPE
6. ALKALI MANGERITE OF HURUM TYPE
7. VOLCANIC EQUIVALENTS OF AKER TYPE
8. MUGEARITE
9. VOLCANIC EQUIVALENTS OF HURUM TYPE
III. AVERAGE ALKALI MANGERITE
IV. AVERAGE ALKALI DOREITE

TABLE 6.—DIORITES AND ANDESITES

| | 1. | 2. | 3. | I. | II. | III. | IV. |
|---|---|---|---|---|---|---|---|
| $SiO_2$ | 52·97 | 48·55 | 52·63 | 51·86 | 54·20 | 51·43 | 47·63 |
| $TiO_2$ | 1·60 | 1·91 | 1·29 | 1·50 | 1·31 | 2·60 | 2·84 |
| $Al_2O_3$ | 18·19 | 16·52 | 15·58 | 16·40 | 17·17 | 13·05 | 14·57 |
| $Fe_2O_3$ | 1·97 | 3·16 | 2·27 | 2·73 | 3·48 | 3·36 | 3·97 |
| $FeO$ | 6·29 | 8·00 | 6·94 | 6·97 | 5·49 | 9·74 | 7·83 |
| $MnO$ | 0·13 | 0·22 | 0·17 | 0·18 | 0·15 | 0·19 | 0·18 |
| $MgO$ | 4·75 | 6·71 | 6·88 | 6·12 | 4·36 | 5·28 | 7·25 |
| $CaO$ | 7·61 | 9·49 | 8·65 | 8·40 | 7·92 | 8·78 | 9·48 |
| $Na_2O$ | 3·50 | 3·10 | 3·16 | 3·36 | 3·67 | 3·18 | 3·75 |
| $K_2O$ | 1·65 | 0·95 | 1·42 | 1·33 | 1·11 | 1·04 | 1·20 |
| $H_2O+$ | 1·00 | 1·11 | 0·56 | 0·80 | 0·86 | 0·87 | 0·78 |
| $P_2O_5$ | 0·34 | 0·28 | 0·45 | 0·35 | 0·28 | 0·48 | 0·52 |
| qz | 2·2 | — | 0·6 | 0·3 | 5·7 | 3·2 | — |
| or | 9·4 | 5·6 | 8·3 | 7·8 | 6·7 | 6·1 | 7·2 |
| ab | 29·3 | 26·2 | 26·7 | 28·3 | 30·9 | 27·2 | 27·2 |
| an | 29·2 | 28·4 | 24·2 | 25·8 | 27·2 | 18·1 | 19·5 |
| ne | — | — | — | — | — | — | 2·3 |
| $CaSiO_3$ | 2·7 | 7·1 | 6·6 | 5·6 | 4·2 | 9·2 | 10·1 |
| $MgSiO_3$ | 11·9 | 9·2 | 17·2 | 15·3 | 10·9 | 13·2 | 6·8 |
| $FeSiO_3$ | 7·5 | 5·0 | 9·0 | 8·5 | 5·3 | 11·1 | 2·5 |
| $Mg_2SiO_4$ | — | 5·3 | — | — | — | — | 8·0 |
| $Fe_2SiO_4$ | — | 3·3 | — | — | — | — | 3·3 |
| mt | 3·0 | 4·6 | 3·3 | 3·9 | 5·1 | 4·9 | 5·8 |
| il | 3·0 | 3·6 | 2·4 | 2·9 | 2·4 | 5·0 | 5·3 |
| ap | 0·8 | 0·7 | 1·0 | 0·8 | 0·7 | 1·1 | 1·2 |
| No. of analyses | (16) | (10) | (11) | (50) | (49) | (26) | (37) |

1. HORNBLENDE-BIOTITE DIORITE
2. HORNBLENDE DIORITE + HORNBLENDE-AUGITE DIORITE
3. PYROXENE-MICA DIORITE
I. AVERAGE DIORITE
II. AVERAGE ANDESITE
III. AVERAGE THOLEIITIC ANDESITE
IV. AVERAGE ALKALI ANDESITE

TABLE 7.—GABBROS AND RELATED ROCKS, BASALTS

| | 1. | 2. | 3. | I. | II. | III. | IV. | V. | VI. |
|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 48·01 | 50·78 | 46·83 | 48·36 | 50·28 | 43·94 | 54·54 | 49·98 | 43·84 |
| $TiO_2$ | 1·55 | 1·15 | 0·97 | 1·32 | 0·89 | 2·86 | 0·52 | 0·14 | 0·67 |
| $Al_2O_3$ | 17·22 | 15·68 | 17·38 | 16·84 | 17·07 | 14·87 | 25·72 | 28·94 | 13·46 |
| $Fe_2O_3$ | 2·90 | 2·26 | 1·91 | 2·55 | 1·30 | 4·35 | 0·83 | 0·80 | 2·20 |
| $FeO$ | 7·68 | 7·41 | 8·20 | 7·92 | 7·46 | 7·80 | 1·46 | 1·43 | 9·24 |
| $MnO$ | 0·15 | 0·18 | 0·14 | 0·18 | 0·14 | 0·15 | 0·02 | 0·01 | 0·15 |
| $MgO$ | 7·45 | 8·35 | 10·03 | 8·06 | 9·27 | 9·31 | 0·83 | 0·84 | 19·71 |
| $CaO$ | 10·80 | 10·85 | 11·36 | 11·07 | 9·72 | 12·37 | 9·62 | 14·01 | 8·16 |
| $Na_2O$ | 2·28 | 2·14 | 2·03 | 2·26 | 1·96 | 2·32 | 4·66 | 2·75 | 1·33 |
| $K_2O$ | 0·53 | 0·56 | 0·40 | 0·55 | 0·63 | 0·92 | 1·06 | 0·42 | 0·58 |
| $H_2O+$ | 1·10 | 0·48 | 0·63 | 0·64 | 0·47 | 0·66 | 0·63 | 0·55 | 0·50 |
| $P_2O_5$ | 0·33 | 0·18 | 0·12 | 0·24 | 0·21 | 0·44 | 0·11 | 0·09 | 0·18 |
| qz | — | 0·9 | — | — | — | — | 1·4 | 1·7 | — |
| or | 2·8 | 3·3 | 2·2 | 3·3 | 3·3 | 5·6 | 6·7 | 2·2 | 3·3 |
| ab | 19·4 | 17·8 | 17·3 | 18·9 | 16·8 | 12·1 | 39·3 | 23·1 | 11·5 |
| an | 35·3 | 31·7 | 37·2 | 34·2 | 37·8 | 27·5 | 45·9 | 65·3 | 28·9 |
| ne | — | — | — | — | — | 4·0 | — | — | — |
| $CaSiO_3$ | 6·7 | 8·8 | 7·7 | 8·0 | 3·7 | 13·0 | 0·3 | 1·5 | 4·4 |
| $MgSiO_3$ | 15·4 | 20·9 | 7·8 | 14·0 | 21·4 | 9·3 | 2·1 | 2·1 | 3·1 |
| $FeSiO_3$ | 7·9 | 10·3 | 3·9 | 7·4 | 10·6 | 2·5 | 1·2 | 1·8 | 0·9 |
| $Mg_2SiO_4$ | 2·2 | — | 12·0 | 4·3 | 1·3 | 9·8 | — | — | 32·3 |
| $Fe_2SiO_4$ | 1·2 | — | 6·5 | 2·5 | 0·6 | 2·9 | — | — | 10·2 |
| mt | 4·2 | 3·3 | 2·8 | 3·7 | 1·9 | 6·3 | 1·2 | 1·2 | 3·2 |
| il | 2·9 | 2·1 | 1·8 | 2·4 | 1·7 | 5·5 | 0·9 | 0·3 | 1·4 |
| ap | 0·8 | 0·4 | 0·3 | 0·6 | 0·5 | 1·0 | 0·3 | 0·2 | 0·4 |
| No. of analyses | (15) | (38) | (53) | (160) | (39) | (42) | (9) | (8) | (9) |

1. HORNBLENDE GABBRO
2. PYROXENE GABBRO
3. OLIVINE GABBRO
I. AVERAGE GABBRO
II. AVERAGE NORITE
III. AVERAGE ALKALI GABBRO
IV. ANORTHOSITE (the massifs)
V. ANORTHOSITE (localised)
VI. TROCTOLITE

TABLE 7.—*Continued*

| VII. | VIII. | IX | X. | XI. | XII. |
|---|---|---|---|---|---|
| 50·83 | 47·90 | 45·78 | 46·77 | 43·69 | 51·33 |
| 2·03 | 1·65 | 2·63 | 3·00 | 2·12 | 1·10 |
| 14·07 | 11·84 | 14·64 | 14·65 | 9·06 | 18·04 |
| 2·88 | 2·32 | 3·16 | 3·71 | 3·46 | 3·40 |
| 9·00 | 9·80 | 8·73 | 7·94 | 9·43 | 5·70 |
| 0·18 | 0·15 | 0·20 | 0·15 | 0·16 | 0·16 |
| 6·34 | 14·07 | 9·39 | 6·82 | 19·68 | 6·01 |
| 10·42 | 9·29 | 10·74 | 12·42 | 9·18 | 10·07 |
| 2·23 | 1·66 | 2·63 | 2·59 | 1·49 | 2·76 |
| 0·82 | 0·54 | 0·95 | 1·07 | 0·69 | 0·82 |
| 0·91 | 0·59 | 0·76 | 0·51 | 0·74 | 0·45 |
| 0·23 | 0·19 | 0·39 | 0·37 | 0·30 | 0·16 |
| 3·5 | — | — | — | — | 2·2 |
| 5·0 | 2·8 | 6·1 | 6·7 | 3·9 | 5·0 |
| 18·9 | 14·1 | 18·3 | 19·4 | 11·0 | 23·6 |
| 25·9 | 23·4 | 24·7 | 25·0 | 16·1 | 33·9 |
| — | — | 2·3 | 1·4 | 0·9 | — |
| 10·3 | 9·1 | 10·8 | 14·2 | 11·5 | 6·4 |
| 15·8 | 20·5 | 7·1 | 9·4 | 8·4 | 15·0 |
| 11·2 | 7·9 | 2·9 | 3·7 | 2·0 | 6·1 |
| — | 10·3 | 11·5 | 5·4 | 28·6 | — |
| — | 4·4 | 5·0 | 2·1 | 7·1 | — |
| 4·2 | 3·3 | 4·6 | 5·3 | 5·1 | 4·9 |
| 3·8 | 3·2 | 5·0 | 5·8 | 4·0 | 2·1 |
| 0·5 | 0·4 | 1·0 | 0·9 | 0·6 | 0·3 |
| (137) | (28) | (96) | (22) | (31) | (56) |
| NORMAL THOLEIITIC BASALT (AND DOLERITE) | THOLEIITIC OLIVINE BASALT | NORMAL ALKALI BASALT (AND DOLERITE) | ALKALI BASALT WITHOUT OLIVINE | OLIVINE-RICH ALKALI BASALT | "CENTRAL" BASALT |

TABLE 8.—PERKNITES

| | 1. | 2. | 3. | 4. | I. | II. | 5. | 6. | 7. | 8. | 9. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 48·86 | 54·65 | 51·84 | 45·02 | 50·50 | 41·55 | 43·72 | 41·83 | 49·67 | 42·00 | 45·40 |
| $TiO_2$ | 0·89 | 0·17 | 0·32 | 1·00 | 0·53 | 3·31 | 2·51 | 1·54 | 0·67 | 2·86 | 1·83 |
| $Al_2O_3$ | 4·53 | 2·19 | 4·47 | 4·38 | 4·10 | 7·25 | 7·54 | 14·94 | 7·01 | 11·39 | 8·38 |
| $Fe_2O_3$ | 1·93 | 0·90 | 2·23 | 4·40 | 2·44 | 6·80 | 5·55 | 4·09 | 2·64 | 5·27 | 5·05 |
| FeO | 4·82 | 8·63 | 7·32 | 8·02 | 7·37 | 7·77 | 5·67 | 5·28 | 9·10 | 10·30 | 7·72 |
| MnO | 0·13 | 0·15 | 0·14 | 0·09 | 0·13 | 0·20 | 0·17 | 0·18 | 0·15 | 0·24 | 0·20 |
| MgO | 15·35 | 31·08 | 21·41 | 19·04 | 21·71 | 13·02 | 14·20 | 15·13 | 22·80 | 12·35 | 16·83 |
| CaO | 21·89 | 1·60 | 10·99 | 16·91 | 12·00 | 16·93 | 15·47 | 13·81 | 6·50 | 11·31 | 12·02 |
| $Na_2O$ | 0·55 | 0·14 | 0·56 | 0·36 | 0·45 | 1·38 | 0·68 | 0·84 | 0·70 | 1·80 | 1·08 |
| $K_2O$ | 0·34 | 0·08 | 0·17 | 0·27 | 0·21 | 0·70 | 2·76 | 0·35 | 0·13 | 0·84 | 0·39 |
| $H_2O+$ | 0·63 | 0·31 | 0·49 | 0·42 | 0·47 | 0·50 | 0·77 | 0·95 | 0·42 | 1·31 | 0·94 |
| $P_2O_5$ | 0·08 | 0·10 | 0·06 | — | 0·09 | 0·59 | 0·74 | 0·06 | 0·11 | 0·33 | 0·16 |
| F | — | — | — | — | — | — | 0·38 | — | — | — | — |
| or | — | 0·6 | 1·1 | — | 1·1 | — | 2·8 | 2·2 | 0·6 | 5·00 | 2·2 |
| ab | — | 1·0 | 4·7 | — | 3·7 | — | — | 3·7 | 5·8 | 8·9 | 9·4 |
| an | 8·9 | 5·3 | 9·2 | 9·5 | 8·6 | 11·4 | 9·2 | 35·6 | 15·8 | 20·6 | 16·7 |
| lc | 1·3 | — | — | 1·3 | — | 3·0 | 10·9 | — | — | — | — |
| ne | 2·6 | — | — | 1·7 | — | 6·5 | 3·1 | 2·0 | — | 3·4 | — |
| $CaSiO_3$ | 37·9 | 0·9 | 18·8 | 29·0 | 21·0 | 27·4 | 25·0 | 13·4 | 6·5 | 13·9 | 17·5 |
| $MgSiO_3$ | 29·2 | 70·3 | 44·9 | 21·5 | 40·4 | 21·8 | 20·7 | 10·7 | 41·8 | 9·6 | 20·6 |
| $FeSiO_3$ | 4·6 | 13·2 | 9·4 | 4·6 | 8·1 | 2·4 | 1·2 | 1·2 | 10·3 | 3·2 | 3·4 |
| $Ca_2SiO_4$ | 2·6 | — | — | 1·5 | — | 1·1 | — | — | — | — | — |
| $Mg_2SiO_4$ | 6·4 | 5·2 | 6·0 | 18·3 | 9·7 | 7·6 | 10·4 | 18·9 | 10·6 | 14·8 | 15·1 |
| $Fe_2SiO_4$ | 1·2 | 1·4 | 1·4 | 3·7 | 2·1 | 0·8 | 0·8 | 2·4 | 2·9 | 5·5 | 3·0 |
| mt | 2·8 | 1·4 | 3·2 | 6·5 | 3·5 | 10·0 | 7·9 | 6·0 | 3·7 | 7·7 | 7·4 |
| il | 1·7 | 0·3 | 0·6 | 2·0 | 1·1 | 6·2 | 4·7 | 2·9 | 1·2 | 5·5 | 3·5 |
| ap | 0·2 | 0·2 | 0·2 | — | 0·2 | 1·3 | 1·7 | 0·2 | 0·3 | 0·8 | 0·3 |
| ft | — | — | — | — | — | — | 0·8 | — | — | — | — |
| No. of analyses | (7) | (9) | (20) | (8) | (46) | (21) | (17) | (9) | (4) | (15) | (5) |

1. Pyroxenite (with rutile)
2. Pyroxenite (with rhombic pyroxene)
3. Pyroxenite (with two pyroxenes)
4. Olivine pyroxenite
I. Average pyroxenite
II. Average alkali pyroxenite
5. Biotite pyroxenite
6. Arkegite
7. Hornblende hypersthenite
8. Hornblendite
9. Olivine hornblendite

TABLE 9.—DUNITES AND PERIDOTITES

| | 1. | 2. | 3. | 4. | 5. | I. | II. | II A. | 6. | 6a. | 7. | 7a. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 40·16 | 35·46 | 26·17 | 43·07 | 42·43 | 43·54 | 40·27 | 41·96 | 35·01 | 38·76 | 36·33 | 39·45 |
| $TiO_2$ | 0·20 | 0·03 | 5·97 | 0·25 | 0·96 | 0·81 | 1·30 | 1·35 | 1·22 | 1·35 | 1·89 | 2·05 |
| $Al_2O_3$ | 0·84 | 1·53 | 2·34 | 4·20 | 5·50 | 3·99 | 7·29 | 7·59 | 3·90 | 4·32 | 5·09 | 5·53 |
| $Fe_2O_3$ | 1·88 | 0·03 | 13·06 | 2·19 | 2·62 | 2·51 | 4·28 | 4·46 | 5·15 | 5·70 | 7·43 | 8·07 |
| FeO | 11·87 | 38·07 | 28·72 | 9·40 | 9·90 | 9·84 | 9·08 | 9·46 | 4·44 | 4·58 | 3·40 | 3·69 |
| MnO | 0·21 | 0·72 | 0·40 | 0·26 | — | 0·21 | 0·25 | 0·26 | 0·06 | 0·07 | 0·10 | 0·11 |
| MgO | 43·16 | 22·09 | 21·95 | 36·43 | 30·79 | 34·02 | 24·31 | 25·32 | 31·29 | 34·63 | 26·63 | 28·91 |
| CaO | 0·75 | 1·43 | 0·57 | 2·98 | 4·78 | 3·46 | 7·15 | 7·45 | 6·80 | 7·53 | 6·78 | 7·36 |
| $Na_2O$ | 0·31 | 0·26 | 0·34 | 0·38 | 0·81 | 0·56 | 1·06 | 1·10 | 0·34 | 0·38 | 0·37 | 0·40 |
| $K_2O$ | 0·14 | tr. | 0·14 | 0·15 | 0·44 | 0·25 | 0·62 | 0·65 | 1·05 | 1·16 | 2·43 | 2·64 |
| $H_2O+$ | 0·44 | 0·35 | 0·34 | 0·64 | 1·69 | 0·76 | 3·67 | — | 7·43 | (0·56) | 7·25 | (1·07) |
| $P_2O_5$ | 0·04 | 0·01 | tr. | 0·05 | 0·08 | 0·05 | 0·38 | 0·40 | 0·87 | 0·96 | 0·66 | 0·72 |
| $CO_2$ | — | — | — | — | — | — | 0·34 | — | 2·73 | — | 1·64 | — |
| or | 0·6 | tr. | 0·6 | 1·1 | 2·8 | 1·7 | | 3·9 | | — | | — |
| ab | 2·1 | — | — | 3·1 | 6·8 | 4·7 | | 6·3 | | — | | — |
| an | 0·6 | 3·0 | 2·8 | 9·2 | 10·0 | 7·5 | | 13·9 | | 6·4 | | 5·6 |
| lc | — | — | — | — | — | — | | — | | 5·7 | | 12·2 |
| ne | 0·3 | 1·1 | 1·4 | — | — | — | | 1·7 | | 1·7 | | 1·7 |
| C | — | — | 0·7 | — | — | — | | — | | — | | — |
| $CaSiO_3$ | 1·1 | 0·9 | — | 2·3 | 5·6 | 3·9 | | 8·5 | | 6·2 | | 9·9 |
| $MgSiO_3$ | 0·9 | 0·4 | — | 12·3 | 6·8 | 14·8 | | 6·4 | | 5·2 | | 8·5 |
| $FeSiO_3$ | 0·1 | 0·5 | — | 2·0 | 1·3 | 2·6 | | 1·2 | | 0·1 | | — |
| $Ca_2SiO_4$ | — | 1·2 | — | — | — | — | | — | | 3·0 | | 0·9 |
| $Mg_2SiO_4$ | 74·9 | 38·3 | 38·5 | 55·2 | 49·1 | 49·1 | | 39·8 | | 57·0 | | 44·7 |
| $Fe_2SiO_4$ | 15·7 | 54·4 | 25·3 | 10·6 | 10·2 | 9·6 | | 8·4 | | 0·7 | | — |
| mt | 2·8 | tr. | 19·0 | 3·2 | 3·7 | 3·7 | | 6·5 | | 8·4 | | 6·3 |
| il | 0·5 | tr. | 11·4 | 0·5 | 1·8 | 1·5 | | 2·6 | | 2·6 | | 3·8 |
| ap | 0·1 | tr. | tr. | 0·1 | 0·2 | 0·1 | | 1·0 | | 2·3 | | 1·7 |
| hm | — | — | — | — | — | — | | — | | — | | 3·8 |
| No. of analyses | (9) | (2) | (7) | (11) | (5) | (23) | (12) | | (10) | | (4) | |

1. DUNITE
2. HORTONOLITE DUNITE
3. ORE DUNITE
4. PYROXENE PERIDOTITE
5. HORNBLENDE PERIDOTITE
I. AVERAGE PERIDOTITE
II. AVERAGE ALKALI PERIDOTITE
II A. AVERAGE ALKALI PERIDOTITE (minus $H_2O+$ and $CO_2$)
6. "BASALTIC" KIMBERLITE
6a. "BASALTIC" KIMBERLITE (minus $CO_2$ and $H_2O+$)
7. "MICACEOUS" KIMBERLITE
7a. "MICACEOUS" KIMBERLITE (minus $CO_2$ and excess $H_2O+$)

TABLE 10.—NEPHELINE SYENITES AND PHONOLITE: NEPHELINE MONZONITE AND NEPHELINE LATITE

| | NEPHELINE SYENITES AND PHONOLITE | | | | | | | NEPHELINE MONZONITE AND NEPHELINE LATITE | |
|---|---|---|---|---|---|---|---|---|---|
| | 1. | 2. | 3. | 4. | I. | II. | III. | IV. | V. |
| $SiO_2$ | 53·11 | 55·14 | 55·84 | 56·47 | 55·38 | 47·42 | 56·90 | 50·38 | 52·95 |
| $TiO_2$ | 0·83 | 0·68 | 0·43 | 0·43 | 0·66 | 1·66 | 0·59 | 2·49 | 1·43 |
| $Al_2O_3$ | 21·39 | 21·22 | 21·07 | 21·26 | 21·30 | 16·03 | 20·17 | 19·97 | 19·14 |
| $Fe_2O_3$ | 2·54 | 1·46 | 2·49 | 3·37 | 2·42 | 5·68 | 2·26 | 2·77 | 3·25 |
| FeO | 1·59 | 2·10 | 2·66 | 1·44 | 2·00 | 5·16 | 1·85 | 3·96 | 2·86 |
| MnO | 0·12 | 0·23 | 0·17 | 0·16 | 0·19 | 0·25 | 0·19 | 0·13 | 0·20 |
| MgO | 0·71 | 0·50 | 0·60 | 0·33 | 0·57 | 3·35 | 0·58 | 2·15 | 2·02 |
| CaO | 2·89 | 1·97 | 1·68 | 1·50 | 1·98 | 6·99 | 1·88 | 6·01 | 5·33 |
| $Na_2O$ | 5·98 | 9·13 | 9·74 | 11·63 | 8·84 | 7·67 | 8·72 | 6·35 | 6·55 |
| $K_2O$ | 9·23 | 5·26 | 3·88 | 2·21 | 5·34 | 3·50 | 5·42 | 3·97 | 4·37 |
| $H_2O+$ | 0·79 | 0·87 | 1·02 | 0·77 | 0·96 | 1·36 | 0·96 | 1·37 | 1·12 |
| $P_2O_5$ | 0·31 | 0·16 | 0·17 | 0·08 | 0·19 | 0·71 | 0·17 | 0·45 | 0·37 |
| $CO_2$ | 0·26 | 0·11 | 0·23 | 0·24 | 0·17 | 0·22 | — | — | — |
| Cl | 0·07 | 0·14 | 0·02 | 0·14 | — | — | 0·23 | — | 0·09 |
| $SO_3$ | 0·18 | 0·06 | — | — | — | — | 0·13 | — | 0·34 |
| or | 54·5 | 31·1 | 22·8 | 12·8 | 31·1 | 20·6 | 31·7 | 23·4 | 26·1 |
| ab | 4·7 | 30·9 | 41·4 | 52·9 | 32·0 | 13·6 | 36·2 | 23·6 | 29·3 |
| an | 5·0 | 2·2 | 2·5 | — | 2·8 | — | 1·7 | 14·5 | 11·1 |
| lc | — | — | — | — | — | — | — | — | — |
| ne | 24·1 | 24·1 | 22·2 | 24·1 | 23·3 | 26·7 | 18·7 | 16·2 | 12·5 |
| ac | — | — | — | — | — | 1·8 | — | — | — |
| $CaSiO_3$ | 2·4 | 2·5 | 1·5 | 2·3 | 2·1 | 12·1 | 2·9 | 5·2 | 5·4 |
| $MgSiO_3$ | 1·8 | 1·2 | 0·6 | 0·8 | 1·2 | 8·2 | 1·4 | 3·9 | 4·4 |
| $FeSiO_3$ | — | 0·9 | 0·9 | — | 0·8 | 2·8 | 0·9 | 0·8 | 0·4 |
| $Mg_2SiO_4$ | — | — | 0·6 | — | 0·1 | 0·1 | — | 1·1 | 0·4 |
| $Fe_2SiO_4$ | — | — | 1·1 | — | 0·1 | 4·1 | — | 0·2 | 0·1 |
| mt | 3·2 | 3·7 | 3·7 | 3·9 | 3·5 | 7·4 | 3·3 | 4·2 | 4·9 |
| il | 1·5 | 1·4 | 0·8 | 0·8 | 1·4 | 3·2 | 1·2 | 4·7 | 2·7 |
| ap | 0·7 | 0·3 | 0·3 | 0·2 | 0·4 | 1·7 | 0·3 | 1·0 | 0·9 |
| hm | 0·3 | — | — | 0·6 | — | — | — | — | — |
| cc | 0·6 | 0·2 | 0·5 | 0·5 | 0·4 | 0·5 | — | — | — |
| NaCl | 0·1 | 0·2 | tr. | 0·2 | — | — | 0·4 | — | 0·1 |
| $Na_2SO_4$ | 0·3 | 0·1 | — | — | — | — | 0·3 | — | 0·6 |
| No. of analyses | (10) | (38) | (8) | (9) | (80) | (25) | (47) | (7) | (16) |

1. NEPHELINE SYENITE (JUVET TYPE)
2. NEPHELINE SYENITE (FOYA TYPE)
3. NEPHELINE SYENITE (LITCHFIELD TYPE)
4. NEPHELINE SYENITE (MARIUPOL TYPE)
I. AVERAGE NEPHELINE SYENITE
II. AVERAGE MALIGNITE
III. AVERAGE PHONOLITE
IV. AVERAGE NEPHELINE MONZONITE
V. AVERAGE NEPHELINE LATITE

TABLE 10A.—NEPHELINE SYENITES AND MALIGNITES

| | NEPHELINE SYENITE | | | | | | | | MALIGNITE | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1. | 2. | 3. | 4. | 5. | 6. | 7. | 8. | 9. | 10. | 11. |
| $SiO_2$ | 55·59 | 56·54 | 53·89 | 55·31 | 54·45 | 53·35 | 53·55 | 57·33 | 52·92 | 44·55 | 46·65 |
| $TiO_2$ | 0·37 | 1·13 | 1·12 | 0·79 | 0·82 | 0·97 | 0·49 | 0·49 | 1·13 | 1·77 | 2·11 |
| $Al_2O_3$ | 21·45 | 20·63 | 19·77 | 21·08 | 21·49 | 18·99 | 21·61 | 22·75 | 15·24 | 17·51 | 14·69 |
| $Fe_2O_3$ | 2·73 | 2·53 | 2·12 | 2·28 | 3·09 | 2·49 | 2·57 | 0·66 | 8·91 | 3·69 | 5·20 |
| FeO | 1·32 | 2·07 | 2·41 | 2·13 | 1·65 | 2·90 | 3·94 | 2·42 | 1·74 | 7·36 | 4·60 |
| MnO | 0·23 | 0·31 | 0·10 | 0·14 | 0·12 | 0·24 | 0·14 | 0·19 | 0·61 | 0·27 | 0·22 |
| MgO | 0·33 | 0·72 | 0·88 | 0·42 | 0·54 | 1·87 | 0·68 | 0·34 | 0·56 | 3·80 | 4·83 |
| CaO | 1·41 | 1·49 | 3·71 | 2·45 | 2·38 | 3·38 | 2·59 | 0·96 | 2·57 | 8·47 | 8·74 |
| $Na_2O$ | 9·98 | 8·87 | 7·51 | 8·43 | 8·06 | 7·92 | 8·67 | 8·66 | 10·59 | 7·33 | 6·12 |
| $K_2O$ | 4·89 | 4·85 | 5·33 | 5·73 | 6·36 | 5·72 | 3·89 | 5·19 | 3·10 | 3·59 | 4·32 |
| $H_2O+$ | 1·03 | 0·77 | 2·09 | 0·91 | 0·64 | 1·24 | 1·20 | 0·67 | 2·15 | 0·85 | 1·09 |
| $P_2O_5$ | 0·04 | 0·09 | 0·20 | 0·13 | 0·26 | 0·75 | 0·26 | 0·03 | 1·12 | 0·80 | 1·28 |
| $CO_2$ | — | — | 0·87 | — | 0·14 | 0·18 | 0·41 | 0·31 | — | — | 0·15 |
| F | 0·25 | — | — | 0·10 | — | — | — | — | — | — | — |
| Cl | 0·23 | — | — | — | — | — | — | — | — | — | — |
| $SO_3$ | 0·07 | — | — | — | — | — | — | — | — | — | — |
| $ZrO_2$ | 0·24 | — | — | — | — | — | — | — | 0·48 | — | — |
| or | 18·9 | 28·4 | | 33·9 | 37·8 | 33·9 | | 30·6 | 18·3 | 19·5 | 25·6 |
| ab | 35·6 | 38·8 | | 28·3 | 23·6 | 22·5 | | 40·4 | 19·9 | — | 6·3 |
| an | — | 2·2 | | 2·8 | 3·6 | — | | 2·8 | — | 4·4 | — |
| lc | — | — | | — | — | — | | — | — | 1·3 | — |
| ne | 25·6 | 19·6 | | 23·3 | 24·1 | 23·3 | | 17·9 | 22·1 | 33·5 | 24·4 |
| C | — | — | | — | — | — | | 1·8 | — | — | — |
| $CaSiO_3$ | 2·1 | 2·0 | | 3·2 | 2·3 | 4·6 | | — | 5·3 | 13·5 | 14·3 |
| $MgSiO_3$ | 0·8 | 1·5 | | 1·0 | 1·3 | 2·9 | | — | 1·4 | 7·1 | 11·6 |
| $FeSiO_3$ | — | 0·3 | | 1·2 | — | 1·5 | | — | 2·2 | 5·9 | 1·0 |
| ac | — | — | | — | — | 0·9 | | — | 25·4 | — | — |
| $Mg_2SiO_4$ | — | 0·2 | | — | — | 1·3 | | 0·6 | — | 1·7 | 0·4 |
| $Fe_2SiO_4$ | — | 0·1 | | — | — | 0·6 | | 2·7 | — | 1·6 | 0·1 |
| mt | 3·7 | 3·7 | | 3·3 | 3·3 | 3·2 | | 0·9 | 0·2 | 5·3 | 7·7 |
| il | 0·8 | 2·1 | | 1·5 | 1·5 | 1·8 | | 0·9 | 2·1 | 3·3 | 4·0 |
| ap | 0·1 | 0·2 | | 0·3 | 0·7 | 1·8 | | tr. | — | 1·9 | 3·0 |
| hm | 0·2 | — | | — | 0·8 | — | | — | — | — | — |
| cc | — | — | | — | 0·3 | 0·4 | | 0·7 | — | — | 0·3 |
| fl | 0·5 | — | | 0·2 | — | — | | — | — | — | — |
| hl | 0·3 | — | | — | — | — | | — | — | — | — |
| py | 0·4 | — | | — | — | — | | — | 0·7 | — | — |
| No. of analyses | (24) | (9) | (3) | (11) | (14) | (5) | (6) | (6) | (4) | (6) | (9) |
| | WITH AEGIRINE-AUGITE (OR AEGIRINE) | WITH AEGIRINE-AUGITE (OR AEGIRINE) AND SODA-AMPHIBOLE | WITH TITANAUGITE AND SODA-AMPHIBOLE | WITH SODA-AMPHIBOLE | WITH AEGIRINE-AUGITE (OR AEGIRINE) AND BIOTITE | WITH DIOPSIDIC AUGITE AND BIOTITE | WITH SODA-AMPHIBOLE AND BIOTITE | WITH BIOTITE | WITH AEGIRINE | WITH PYROXENE AND SODA-AMPHIBOLE | WITH PYROXENE AND BIOTITE |

TABLE 11.—ESSEXITE, GLENMUIRITE, THERALITE, TESCHENITE, AND CORRESPONDING LAVAS

| | I. | II. | III. | IV. | V. | VI. | VII. |
|---|---|---|---|---|---|---|---|
| $SiO_2$ | 46·48 | 46·41 | 47·34 | 45·97 | 44·82 | 45·93 | 45·75 |
| $TiO_2$ | 2·81 | 2·43 | 2·53 | 2·34 | 2·65 | 2·13 | 2·36 |
| $Al_2O_3$ | 17·07 | 15·66 | 16·59 | 16·64 | 15·42 | 16·25 | 17·07 |
| $Fe_2O_3$ | 3·62 | 4·28 | 4·50 | 2·94 | 4·28 | 3·81 | 5·44 |
| FeO | 5·94 | 6·31 | 5·72 | 8·27 | 6·61 | 7·36 | 3·82 |
| MnO | 0·16 | 0·22 | 0·20 | 0·26 | 0·16 | 0·20 | 0·14 |
| MgO | 4·85 | 5·40 | 5·04 | 5·73 | 7·27 | 6·13 | 6·36 |
| CaO | 9·49 | 8·13 | 8·65 | 10·45 | 10·32 | 8·83 | 9·67 |
| $Na_2O$ | 5·09 | 4·44 | 5·33 | 5·06 | 5·30 | 3·97 | 4·99 |
| $K_2O$ | 2·64 | 2·47 | 2·63 | 1·37 | 1·26 | 1·34 | 1·25 |
| $H_2O+$ | 0·97 | 3·59 | 0·87 | 0·66 | 1·56 | 3·55 | 2·48 |
| $P_2O_5$ | 0·48 | 0·66 | 0·60 | 0·31 | 0·35 | 0·50 | 0·67 |
| or | 15·6 | 15·0 | 15·6 | 8·3 | 7·8 | 7·8 | 7·8 |
| ab | 14·7 | 21·0 | 18·3 | 13·1 | 12·6 | 24·6 | 22·0 |
| an | 16·1 | 15·3 | 13·6 | 18·4 | 14·5 | 22·5 | 20·3 |
| ne | 15·3 | 9·1 | 14·5 | 16·2 | 17·3 | 4·8 | 10·9 |
| $CaSiO_3$ | 11·6 | 8·7 | 10·7 | 13·2 | 14·3 | 7·7 | 9·5 |
| $MgSiO_3$ | 8·2 | 6·0 | 7·8 | 7·6 | 10·4 | 4·9 | 8·2 |
| $FeSiO_3$ | 2·4 | 2·0 | 1·8 | 5·0 | 2·5 | 2·1 | — |
| $Mg_2SiO_4$ | 2·8 | 5·2 | 3·4 | 4·7 | 5·5 | 7·3 | 5·4 |
| $Fe_2SiO_4$ | 0·8 | 1·9 | 0·8 | 3·4 | 1·5 | 3·9 | — |
| mt | 5·3 | 6·3 | 6·5 | 4·2 | 6·3 | 5·6 | 5·8 |
| il | 5·3 | 4·6 | 4·9 | 4·4 | 5·0 | 4·1 | 4·6 |
| ap | 1·2 | 1·5 | 1·4 | 0·7 | 0·8 | 1·2 | 1·6 |
| hm | — | — | — | — | — | — | 1·4 |
| No. of analyses | (15) | (13) | (27) | (6) | (8) | (8) | (7) |

I. AVERAGE ESSEXITE
II. AVERAGE GLENMUIRITE
III. AVERAGE ORDANCHITE
IV. AVERAGE THERALITE
V. AVERAGE NEPHELINE TEPHRITE
VI. AVERAGE TESCHENITE
VII. AVERAGE ANALCITE TEPHRITE

TABLE 12.—ULTRA-ALKALINE AND RELATED ROCKS

| | I. | II. | III. | IV. | V. | VI. | VII. | VIII. | IX. |
|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 42·59 | 42·58 | 41·90 | 40·85 | 40·90 | 39·07 | 40·29 | 42·87 | 44·95 |
| $TiO_2$ | 0·35 | 1·41 | 2·21 | 2·44 | 3·99 | 3·86 | 2·90 | 2·59 | 3·51 |
| $Al_2O_3$ | 27·42 | 18·46 | 12·20 | 20·46 | 13·65 | 12·82 | 11·32 | 14·67 | 13·52 |
| $Fe_2O_3$ | 2·49 | 4·01 | 6·41 | 2·86 | 6·67 | 8·75 | 4·87 | 3·54 | 5·42 |
| FeO | 1·89 | 4·19 | 4·32 | 5·08 | 7·14 | 6·39 | 7·69 | 7·73 | 5·07 |
| MnO | 0·09 | 0·20 | 0·22 | 0·09 | — | 0·26 | 0·22 | 0·30 | 0·15 |
| MgO | 0·69 | 3·22 | 5·45 | 3·56 | 8·35 | 6·14 | 13·28 | 6·64 | 8·02 |
| CaO | 4·38 | 11·38 | 16·60 | 10·06 | 13·28 | 14·20 | 12·99 | 11·81 | 9·78 |
| $Na_2O$ | 14·12 | 9·55 | 5·10 | 8·71 | 3·06 | 4·09 | 3·14 | 4·69 | 4·65 |
| $K_2O$ | 3·82 | 2·55 | 2·66 | 2·98 | 1·65 | 2·07 | 1·44 | 1·47 | 1·21 |
| $H_2O+$ | 0·42 | 0·55 | 0·87 | 0·98 | 0·50 | 1·59 | 1·08 | 3·34 | 2·80 |
| $P_2O_5$ | 0·44 | 1·52 | 1·24 | 0·53 | 0·81 | 0·76 | 0·78 | 0·35 | 0·92 |
| $CO_2$ | 1·30 | 0·38 | 0·82 | 0·40 | — | — | — | — | — |
| Cl | — | — | — | — | — | — | — | — | — |
| or | 8·3 | 10·0 | 6·7 | — | 9·4 | 1·7 | — | 8·9 | 7·2 |
| ab | — | — | — | — | 1·6 | — | — | 3·1 | 22·5 |
| an | 0·6 | — | 2·5 | 8·1 | 18·6 | 10·3 | 12·8 | 14·5 | 12·2 |
| lc | 10·9 | 3·9 | 7·4 | 13·9 | — | 8·3 | 6·5 | — | — |
| ne | 64·5 | 43·7 | 43·3 | 39·8 | 13·1 | 18·7 | 14·2 | 19·9 | 9·1 |
| ac | — | — | — | — | — | — | — | — | — |
| $CaSiO_3$ | 4·3 | 18·5 | 27·9 | 11·2 | 17·6 | 23·0 | 17·2 | 17·5 | 12·6 |
| $MgSiO_3$ | 1·7 | 8·0 | 13·6 | 8·1 | 14·7 | 15·3 | 13·1 | 11·3 | 10·9 |
| $FeSiO_3$ | 0·9 | 1·4 | — | 2·1 | 0·7 | — | 2·2 | 5·0 | — |
| $Ca_2SiO_4$ | — | — | — | 2·7 | — | — | 1·6 | — | — |
| $Mg_2SiO_4$ | — | — | — | 0·6 | 4·3 | — | 14·1 | 3·8 | 6·3 |
| $Fe_2SiO_4$ | — | — | — | 0·2 | 0·2 | — | 2·7 | 1·8 | — |
| mt | 3·7 | 5·8 | 8·1 | 5·6 | 9·7 | 10·4 | 7·2 | 5·1 | 6·5 |
| il | 0·6 | 2·7 | 4·3 | 4·6 | 7·6 | 7·3 | 5·5 | 5·0 | 6·7 |
| ap | 1·0 | 3·6 | 2·9 | 1·3 | 1·9 | 1·8 | 1·8 | 0·8 | 2·2 |
| hm | — | — | 0·8 | — | — | 1·4 | — | — | 1·0 |
| cc | 3·0 | 0·9 | 1·8 | 0·9 | — | — | — | — | — |
| NaCl | — | — | — | — | — | — | — | — | — |
| No. of analyses | (6) | (11) | (9) | (3) | (3) | (8) | (21) | (4) | (8) |

I. AVERAGE URTITE
II. AVERAGE IJOLITE
III. AVERAGE MELTEIGITE
IV. IJOLITE WITH TITANAUGITE
V. MELTEIGITE WITH TITANAUGITE
VI. AVERAGE NEPHELINITE
VII. AVERAGE OLIVINE NEPHELINITE
VIII. AVERAGE BEKINKINITE
IX. AVERAGE OLIVINE ANALCITITE

* $SO_3$ = 0.36.
† $SO_3$ = 0.06.

TABLE 12.—*Continued*

| X. | XI. | XII. | XIII. | XIV. | XV. | |
|---|---|---|---|---|---|---|
| 43·99 | 33·68 | 38·34 | 39·11 | 37·59 | 37·08 | $SiO_2$ |
| 0·10 | 2·85 | 1·85 | 3·10 | 3·40 | 3·31 | $TiO_2$ |
| 22·25 | 13·43 | 6·07 | 13·54 | 11·09 | 8·08 | $Al_2O_3$ |
| 6·27 | 5·89 | 6·93 | 7·83 | 5·18 | 5·12 | $Fe_2O_3$ |
| 1·99 | 4·33 | 4·62 | 3·51 | 6·77 | 7·23 | FeO |
| 0·06 | 0·29 | 0·20 | 0·32 | 0·35 | 0·18 | MnO |
| 0·52 | 6·37 | 8·12 | 8·25 | 13·47 | 16·19 | MgO |
| 0·94 | 20·76 | 28·98 | 15·81 | 14·73 | 16·30 | CaO |
| 17·90 | 4·40 | 2·25 | 3·55 | 3·62 | 2·30 | $Na_2O$ |
| 1·59 | 2·78 | 0·27 | 2·50 | 1·33 | 1·36 | $K_2O$ |
| 1·19 | 2·25 | 0·55 | 2·06 | 1·45 | 1·89 | $H_2O+$ |
| 0·02 | 1·68 | 0·53 | 0·41 | 1·02 | 0·96 | $P_2O_5$ |
| — | 0·93 | 0·79 | — | — | — | $CO_2$ |
| 4·10 | * | † | — | — | — | Cl |
| 9·4 | — | — | — | — | — | or |
| 8·9 | — | — | — | — | — | ab |
| — | 9·4 | 6·1 | 13·3 | 10·3 | 7·5 | an |
| — | 13·1 | 1·3 | 11·8 | 6·1 | 6·5 | lc |
| 52·3 | 19·0 | 9·9 | 16·2 | 16·5 | 10·5 | ne |
| 13·9 | — | — | — | — | — | ac |
| 2·0 | 2·5 | 20·5 | 14·4 | 11·6 | 10·7 | $CaSiO_3$ |
| 0·7 | 2·2 | 17·6 | 11·4 | 9·4 | 8·6 | $MgSiO_3$ |
| 1·3 | — | 0·1 | — | 0·8 | 0·8 | $FeSiO_3$ |
| — | 21·7 | 24·9 | 8·6 | 8·8 | 12·8 | $Ca_2SiO_4$ |
| 0·4 | 9·7 | 1·8 | 6·4 | 17·0 | 22·3 | $Mg_2SiO_4$ |
| 0·8 | — | 0·1 | — | 1·7 | 2·5 | $Fe_2SiO_4$ |
| 2·1 | 6·5 | 10·0 | 3·3 | 7·7 | 7·4 | mt |
| 0·2 | 5·5 | 3·5 | 5·9 | 6·5 | 6·2 | il |
| tr. | 4·0 | 1·3 | 1·0 | 2·3 | 2·3 | ap |
| — | 1·4 | — | 5·6 | — | — | hm |
| — | 2·1 | 1·8 | — | — | — | cc |
| 6·8 | th 0·6 | th 0·1 | — | — | — | NaCl |
| (3) | (5) | (1) | (3) | (8) | (10) | No. of analyses |

X. AVERAGE TAWITE

XI. AVERAGE TURJAITE

XII. AVERAGE UNCOMPAHGRITE

XIII. AVERAGE MELILITE NEPHELINITE

XIV. AVERAGE OLIVINE-MELILITE NEPHELINITE

XV. AVERAGE OLIVINE MELILITITE

TABLE 13.—LEUCITIC ROCKS

| | 1. | 2. | 3. | 4. | 5. | 6. | 7. | 8. |
|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 49.24 | 48.55 | 45.08 | 50.54 | 50.07 | 47.05 | 52.28 | 46.75 |
| $TiO_2$ | 1.15 | 1.69 | 2.17 | 0.87 | 1.32 | 1.54 | 0.63 | 1.65 |
| $Al_2O_3$ | 14.99 | 15.55 | 11.35 | 19.17 | 18.43 | 16.05 | 22.29 | 14.02 |
| $Fe_2O_3$ | 2.18 | 1.69 | 4.83 | 3.55 | 2.13 | 3.49 | 1.24 | 3.47 |
| FeO | 4.33 | 5.00 | 4.31 | 3.46 | 4.96 | 5.78 | 0.48 | 3.50 |
| MnO | 0.16 | 0.15 | — | 0.26 | 0.16 | 0.17 | 0.03 | 0.08 |
| MgO | 6.59 | 6.68 | 8.60 | 2.79 | 4.45 | 6.20 | 0.09 | 8.17 |
| CaO | 11.88 | 12.25 | 20.09 | 7.83 | 8.39 | 10.80 | 1.82 | 11.13 |
| $Na_2O$ | 1.53 | 1.93 | 0.75 | 3.31 | 2.44 | 2.35 | 1.47 | 1.76 |
| $K_2O$ | 6.96 | 5.53 | 2.54 | 7.01 | 6.74 | 5.38 | 18.59 | 8.10 |
| $H_2O+$ | 0.49 | 0.55 | 0.20 | 0.61 | 0.57 | 0.60 | 0.43 | 0.71 |
| $P_2O_5$ | 0.50 | 0.43 | 0.08 | 0.43 | 0.34 | 0.59 | 0.10 | 0.66 |
| Cl | — | — | — | 0.19 | — | — | — | — |
| $SO_3$ | — | — | — | — | — | — | 0.55 | — |
| or | 13.3 | 17.8 | — | 41.1 | 39.5 | 22.2 | 2.2 | — |
| ab | — | — | — | 3.1 | 1.1 | — | — | — |
| an | 13.3 | 17.2 | 20.0 | 17.8 | 19.5 | 17.5 | 1.1 | 6.4 |
| lc | 21.8 | 11.8 | 11.8 | — | — | 7.4 | 84.6 | 37.5 |
| ne | 7.1 | 8.8 | 3.4 | 12.5 | 10.5 | 10.8 | 4.8 | 7.9 |
| $CaSiO_3$ | 17.9 | 17.0 | 26.7 | 7.7 | 8.4 | 13.6 | 2.9 | 17.2 |
| $MgSiO_3$ | 12.8 | 11.9 | 21.5 | 5.2 | 5.3 | 9.5 | 0.2 | 14.3 |
| $FeSiO_3$ | 3.4 | 3.7 | 0.4 | 1.9 | 2.5 | 3.2 | — | 0.6 |
| $Ca_2SiO_4$ | — | — | 4.6 | — | — | — | — | 1.0 |
| $Mg_2SiO_4$ | 2.7 | 3.4 | — | 1.3 | 4.1 | 4.3 | — | 4.2 |
| $Fe_2SiO_4$ | 0.8 | 1.0 | — | 0.5 | 2.2 | 1.7 | — | 0.3 |
| mt | 3.2 | 2.6 | 7.0 | 5.1 | 3.0 | 5.1 | — | 5.1 |
| il | 2.1 | 3.2 | 4.1 | 1.7 | 2.4 | 2.9 | 1.1 | 3.2 |
| ap | 1.2 | 1.0 | 0.2 | 1.0 | 0.8 | 1.3 | 0.2 | 1.5 |
| hm | — | — | — | — | — | — | 1.3 | — |
| th | — | — | — | — | — | — | 1.0 | — |
| hl | — | — | — | 0.4 | — | — | — | — |
| sp | — | — | — | — | — | — | 0.2 | — |
| No. of analyses | (4) | (3) | (2) | (16) | (12) | (31) | (2) | (6) |

1. LEUCITE MONZONITE (SOMMAITE)
2. LEUCITE MANGERITE
3. LEUCITE GABBRO (PUGLIANITE)
4. LEUCITE LATITE (includes VICOITE and CAMPANITE)
5. LEUCITE ORBANCHITE
6. LEUCITE TEPHRITE (S.S.) (includes VESUVITE, KIVITE, OTTAJANITE, etc.)
7. ITALITE
8. MESOTYPE MISSOURITE

TABLE 13.—*Continued*

| 9. | 10. | 11. | 12. | 13. | 14. | 15. | |
|---|---|---|---|---|---|---|---|
| 46·87 | 47·11 | 43·64 | 42·74 | 46·02 | 45·78 | 39·77 | $SiO_2$ |
| 1·19 | 1·25 | 2·54 | 2·67 | 3·14 | 0·73 | 2·81 | $TiO_2$ |
| 10·36 | 15·74 | 10·28 | 16·72 | 13·29 | 16·77 | 7·98 | $Al_2O_3$ |
| 2·54 | 4·54 | 5·11 | 4·84 | 5·44 | 4·02 | 6·46 | $Fe_2O_3$ |
| 3·79 | 4·54 | 5·89 | 5·90 | 7·36 | 4·28 | 4·38 | FeO |
| 0·05 | 0·17 | 0·15 | 0·21 | 0·28 | – | 0·20 | MnO |
| 13·31 | 5·14 | 13·86 | 4·43 | 9·06 | 5·15 | 14·60 | MgO |
| 14·73 | 11·01 | 10·66 | 10·73 | 13·17 | 10·86 | 15·20 | CaO |
| 0·90 | 2·02 | 2·16 | 5·46 | 3·37 | 2·40 | 1·35 | $Na_2O$ |
| 5·43 | 6·72 | 4·09 | 5·18 | 3·16 | 8·71 | 4·12 | $K_2O$ |
| 0·53 | 0·87 | 0·72 | 0·52 | 0·90 | 0·61 | 2·95 | $H_2O+$ |
| 0·30 | 0·44 | 0·63 | 0·59 | 0·75 | 0·48 | 0·73 | $P_2O_5$ |
| – | – | – | – | – | – | – | Cl |
| – | – | – | – | – | – | – | $SO_3$ |
| – | 15·3 | 6·9 | – | – | – | – | or |
| – | – | – | – | – | – | – | ab |
| 8·1 | 14·2 | 6·1 | 5·8 | 11·7 | 9·2 | 3·3 | an |
| 25·3 | 19·0 | 13·8 | 24·0 | 14·8 | 40·5 | 19·2 | lc |
| 4·3 | 9·1 | 9·9 | 25·0 | 15·3 | 11·1 | 6·3 | ne |
| 19·6 | 15·7 | 17·8 | 16·2 | 14·2 | 11·0 | 11·4 | $CaSiO_3$ |
| 15·8 | 11·4 | 14·5 | 9·9 | 10·7 | 7·9 | 9·8 | $MgSiO_3$ |
| 1·4 | 2·8 | 1·1 | 2·5 | 2·0 | 2·1 | – | $FeSiO_3$ |
| 5·0 | – | – | 1·5 | 4·6 | 4·7 | 12·4 | $Ca_2SiO_4$ |
| 12·2 | 1·2 | 14·1 | 0·8 | 8·4 | 3·5 | 18·8 | $Mg_2SiO_4$ |
| 1·2 | 0·3 | 1·2 | 0·2 | 1·8 | 1·0 | – | $Fe_2SiO_4$ |
| 3·7 | 6·5 | 7·4 | 7·0 | 7·9 | 5·8 | 6·7 | mt |
| 2·3 | 2·3 | 4·9 | 5·2 | 5·9 | 1·4 | 5·3 | il |
| 0·7 | 1·0 | 1·5 | 1·3 | 1·7 | 1·2 | 1·7 | ap |
| – | – | – | – | – | – | 1·9 | fm |
| – | – | – | – | – | – | – | th |
| – | – | – | – | – | – | – | hl |
| – | – | – | – | – | – | – | sp |
| (5) | (7) | (11) | (6) | (7) | (2) | (5) | No. of analyses |
| MELANOCRATIC MISSOURITE | LEUCITITE | OLIVINE LEUCITITE | ETINDITE | OLIVINE ETINDITE | MELILITE LEUCITITE | OLIVINE-MELILITE LEUCITITE | |

TABLE 14.—GENERAL AVERAGES OF IGNEOUS ROCKS

| | I. | II. | III. | IV. | V. | VI. |
|---|---|---|---|---|---|---|
| $SiO_2$ | 68·9 | 54·5 | 54·6 | 48·2 | 48·4 | 43·8 |
| $TiO_2$ | 0·5 | 1·4 | 1·5 | 1·9 | 1·8 | 1·7 |
| $Al_2O_3$ | 14·5 | 17·2 | 16·4 | 15·6 | 15·5 | 6·1 |
| $Fe_2O_3$ | 1·7 | 3·2 | 3·3 | 3·0 | 2·8 | 4·5 |
| FeO | 2·2 | 4·6 | 5·2 | 7·8 | 8·1 | 8·7 |
| MnO | 0·07 | 0·16 | 0·15 | 0·17 | 0·17 | 0·18 |
| MgO | 1·1 | 3·2 | 3·8 | 8·2 | 8·6 | 22·5 |
| CaO | 2·6 | 5·8 | 6·5 | 10·5 | 10·7 | 10·1 |
| $Na_2O$ | 3·9 | 5·1 | 4·2 | 2·6 | 2·3 | 0·8 |
| $K_2O$ | 3·8 | 3·6 | 3·2 | 0·9 | 0·7 | 0·7 |
| $H_2O+$ | 0·6 | 0·8 | 0·7 | 0·8 | 0·7 | 0·6 |
| $P_2O_5$ | 0·16 | 0·39 | 0·42 | 0·30 | 0·27 | 0·30 |

I. AVERAGE SILICIC IGNEOUS ROCK (794 analyses)

II. AVERAGE INTERMEDIATE IGNEOUS ROCK (INCLUDING NEPHELINE TYPES) (810 analyses)

III. AVERAGE INTERMEDIATE IGNEOUS ROCK (EXCLUDING NEPHELINE TYPES) (635 analyses)

IV. AVERAGE SUBSILIC IGNEOUS ROCK (INCLUDING NEPHELINE TYPES) (721 analyses)

V. AVERAGE SUBSILIC IGNEOUS ROCK (EXCLUDING NEPHELINE TYPES) (637 analyses)

VI. AVERAGE ULTRAMAFIC IGNEOUS ROCK (182 analyses)